Plant Archives Vol. 26, Supplement 2, 2026 pp.707-719 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2026.v26.supplement-2.080

TRANSFORMING FOOD WASTE INTO FUNCTIONAL FOODS: THE ROLE OF 3D PRINTING IN GLOBAL SUSTAINABILITY

Ritu B. Kukde[1], Pratiksha H. Puranik[2]*, Vikram P. Kad[3], Ganesh S. Kahar[2], Thongam Sunita[1] and Ganesh N. Shelke[3]

[1]ICAR-Central Institute of Post-Harvest Engineering and Technology (CIPHET), Ludhiana, Punjab-141001, India
[2]Dr. A.S. College of Agril. Engg & Tech., MPKV, Rahuri (M.S.)-413722, India
[3]Department of Agril. Process Engineering, Dr. A.S. College of Agril. Engg. & Tech., MPKV, Rahuri (M.S.)-413722.
*Corresponding author E-mail: puranikpratiksha98@gmail.com.
(Date of Receiving : 19-02-2026; Date of Revision : 04-04-2026; Date of Acceptance : 24-04-2026)

ABSTRACT

3D printing technology offers a sustainable strategy for food waste valorization within circular economy paradigms. This review explores the transformative potential of 3D Food Printing (3DFP) as a sustainable solution for upcycling food by-products into value-added materials. Global food waste, totalling approximately 931 million tonnes annually, poses severe environmental and economic threats. This paper categorizes diverse waste streams including plant-derived processing waste, marine/animal by-products, and biomass detailing their conversion into functional 3D printing inks. The review examines core technologies such as Fused Deposition Modelling (FDM), Direct Ink Writing (DIW), and Selective Laser Sintering (SLS), emphasizing the optimization of process parameters like nozzle diameter and extrusion speed to enhance structural integrity. Integrating 3DFP into a circular economy framework facilitates localized upcycling, reducing "food miles" and waste disposal volumes by 20–60%. This technology directly aligns with UN Sustainable Development Goals (SDGs 2, 12, and 13) by promoting responsible production and nutrient-dense, customized nutrition. Despite challenges in nutrient stability during shelf-life, 3DFP represents a resilient shift toward zero-waste food systems.
Keywords **:** 3D food printing, food waste upcycling, circular economy, valorization, sustainable development goals, additive manufacturing.

Introduction

Food loss and food waste have significant global issues (Yoha *et al.,* 2023). Food wastage is a major threat to food security, the economy, and the environment, resulting in resource depletion and increasing greenhouse gas emissions (Wong *et al.,* 2022). Waste production in the food sector presents considerable issues, encompassing adverse environmental impacts, improper resource utilization, and significant economic impact (Jagdishwaran *et al.,* 2021). Approximately one-third of global food production is either lost or wasted. Food waste occurs at every level, including agricultural production, industrial processing, retail, and domestic consumption (Wong *et al.,* 2022). Tubers, fruits, and vegetables exhibit the highest waste rates at 40–50%, preceded by fish at 35%, cereals at 30%, and oilseeds, meat, and dairy products at 20% (Molina-Montero *et al.,* 2023). The fruit and vegetable business produces enormous waste rich in nutrients and bioactive substances, such as vitamins, proteins, phenolics, carotenoids, and enzymes (Muthurajan *et al.,* 2021, Pant *et al.*, 2023; and Molina-Montero *et al.*, 2023). Nonetheless, food waste produced in households exceeds that generated by the business, particularly in industrialized nations. The recycling of food waste is labor-intensive and expensive due to the intricate characteristics of food waste and its spatial distribution (Pant *et al.,* 2023).

According to the United Nations Environment Programme's (UNEP) 2021 Food Waste Index, the world produces around 931 million tonnes of food waste annually. This substantial figure derives from multiple sectors, with dwellings accounting for the predominant portion at 61%, around 569 million tonnes. The food service business constitutes 26%, generating around 244 million tons, even with the retail sector contributing 13%, or roughly 118 million tons. These numbers emphasize the important contribution of each industry to the global food waste epidemic and highlight the vital demand for sustainable solutions to reduce waste production and its ecological consequences. Industrial and agricultural waste streams, abundant in nutrients and bioactive substances, can be reutilized to promote sustainable food processing and a zero-waste circular economy. The agricultural industry, covering approximately one-third of the surface of the earth, produces substantial bio-waste, such as rice husk, wheat straw, and sugarcane bagasse. These materials aggravate greenhouse gas emissions, pollution, and several environmental issues. Appropriate bio-waste management and sustainable recycling techniques are crucial for mitigating emissions and addressing issues such as heavy metal pollution, nutrient exploitation, and disease transmission (Yoha *et al.,* 2023; Pant *et al.,* 2023; Rahman *et al.,* 2023; Montero Melino *et al.,* 2023).

The fundamental concepts of a circular economy and zero-waste economy are essential for advocating an ethical, environmentally sensitive lifestyle that favors both humanity and the ecosystem. A fundamental strategy in realizing this objective is a conversion of food waste into value-added products (Wong *et al.,* 2022). The integration of additive manufacturing (AM) with bio-waste encourages sustainable practices like recycling and upcycling, thereby diminishing reliance on petrochemical-derived materials and lowering ecological impact. This integration additionally facilitates economic advantages by advancing a bio-circular economy and supporting sustainable manufacturing practices. Advancements in food science are addressing consumer reluctance toward foods derived from waste by enhancing nutrition, optimizing resources, and promoting sustainability (Jagdishwaran *et al.,* 2021). In the production of personalized meals, innovative textures, and high-value food products, emerging technologies such as 3D food printing (3DFP) are crucial. These technologies utilize by-products such as milling fractions, fruit peels, and other bio-waste. This digitized process complies with zero-waste principles, as it promotes local manufacturing, eliminates transportation footprints, and optimizes the reuse and utilization of food processing waste.

In the food sector, 3D food printing (3DFP) has emerged as a transformative technology, enabling the creation of dishes tailored to specific nutritional and sensory needs. Three-dimensional printing (3DP), also known as additive manufacturing (AM) or rapid prototyping, is a groundbreaking technology that constructs solid objects from digital files through layer-by-layer material deposition. Initially introduced by Cornell University researchers using an extrusion-based printer, 3DP has found applications in fields such as military, space exploration, healthcare, and food production (Liu *et al.* 2017). 3DFP offers customized approaches for athletes, pregnant women, and people with dysphagia through the application of extrudable inks like chocolate, cheese, and hydrogels in combination with non-extrudable meals like vegetables and meat coupled with hydrocolloids. Fig. 1 shows the overview of general work flow involved in 3D food printing. This precision technology improves the aesthetic and nutritional quality of food while providing novel dining experiences (Pant *et al.,* 2023).

3DFP utilizes multiple techniques, such as extrusion-based printing, selective laser sintering (SLS), binder jetting, and inkjet printing, to generate a broad range of food products. Preliminary experiments (2006–2009) have shown its adaptability in producing chocolate figures, cookie dough, cheese profiles, and sugar sculptures utilizing multi-material printers and syringe-like extruders. These advances facilitate the production of complex designs and customized food products (Liu *et al.,* 2017; Varvara *et al.,* 2021). 3DFP expands the variety of food ingredients by including unique sources like insects, high-fiber plant parts, and animal by-products in food inks, allowing for new and creative food combinations. It tackles the time-sensitive issues of the food sector, such as nourishing a growing demographic, fulfilling individualized nutritional requirements, and ensuring environmentally sustainable production. Through the optimization of resource utilization and the minimization of food waste, 3DFP advances sustainable development objectives. Utilizing technologies such as 3DFP is essential for addressing these difficulties and assuring food security and nutrition for all (Rayna and Striukova, 2016; Severini & Derossi, 2016; Tian *et al.,* 2016; Wong *et al.,* 2022; Tyupova *et al*., 2024).

Additionally, 3DFP promotes circular economy approaches by reutilizing agro-industrial by-products to mitigate food waste. Incorporating waste materials into printable food inks provides renewable and efficient solutions that are consistent with the United Nations' Sustainable Development Goals (SDGs). This technology could transform food production, alter supply chains, and enhance sustainability by reducing waste and optimizing resource use (Alami *et al*., 2024). This paper addresses the relevance of sensory attributes, texture, and structure in the reception of 3D-printed foods. It comprises the origins and categories of food waste, the principles of 3D printing technology, and its utilization in waste valorization through conversion of food waste into printable materials. The discussion spans several uses of 3D food printing, including an analysis of the economic viability of this technology, its constraints, advantages, and future potential.

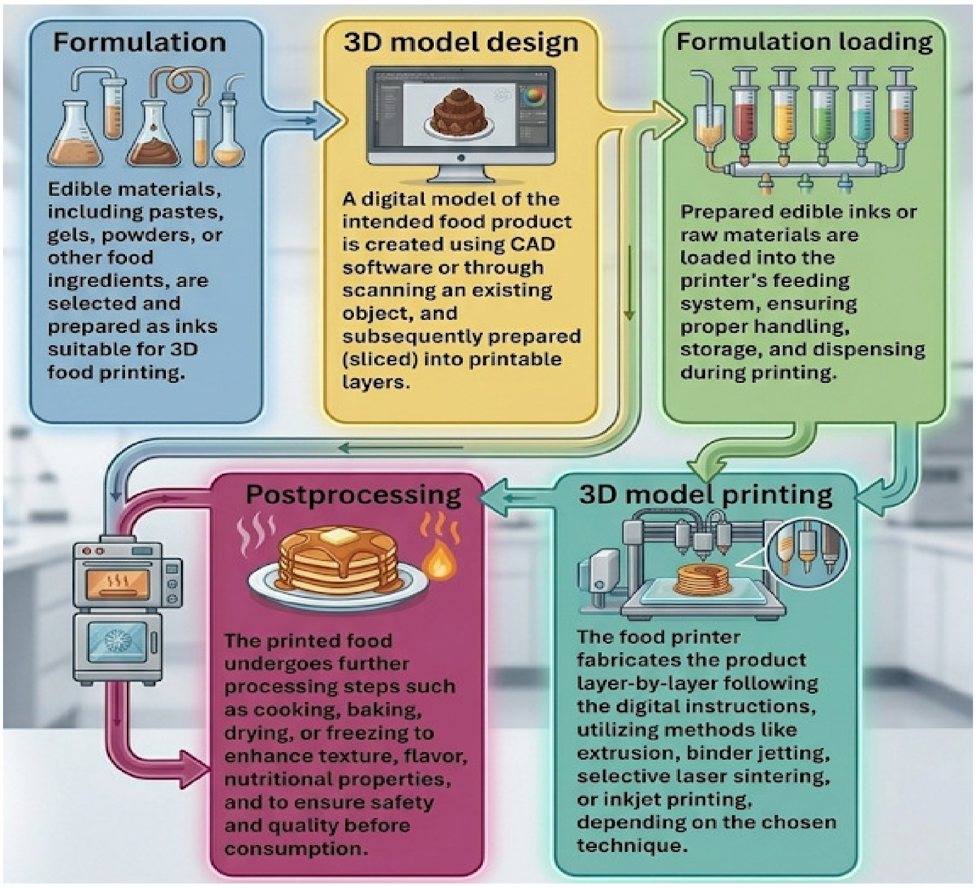

Fig. 1 : Overview of the general workflow involved in 3D food printing

3D Printable Food Materials

The materials used in 3D food printing were classified into four categories: plant-derived, animal and marine-sourced, fermentation and extraction by-products, and biomass. Utilizing these materials, various industries (e.g., food, pharmaceutical, construction) might reduce their dependence on original resources and reduce waste and carbon emissions, thus promoting a more circular and sustainable economy. Table 1. demonstrates the types of materials used, their resources, the 3D food ink matrix, and its weight percentage.

Plant-Derived Processing By-Products and Waste

Plant-derived processing waste contains significant amount of bioactive compounds, cellulose, fibre and starch helpful for the nutritional and technological attributes of printable materials. The addition of fiber-rich powders from broccoli and carrot residues improves snack texture, layer resolution, and printability (Ahmadzadeh *et al.,* 2024). Adding antioxidant- and fiber-dense orange-peel powders to snack and apricot-gel matrices offers nutritional value and improves extrusion and dimensional stability, emphasizing the versatility of plant-processing wastes in 3DP (Da Tan *et al*., 2023; Leo *et al.,* 2022; Molina-Montero *et al.,* 2023). Muthurajan *et al.* (2021) employed potato peels with high starch and fiber content to improve the nutritional value and structural integrity of 3D-printed noodles. Furthermore, okara, a soybean processing by-product, can be used to create 3D printed food products with up to 28% protein content, providing a nutritionally dense and stable alternative for custom food products (Lee *et al.* 2021). Tomato stems and leaves with high density in lignocellulosic material were processed into 3D-printed biocomposites that acted as fertilizers and copper ion absorbers, showcasing their dual role in environmental applications and waste management (Scaffaro *et al.*, 2024).

Microcrystalline cellulose (MCC) from aloe vera peels permits biodegradable 3D-printed hydrogels by enhancing cross-linking and mechanical strength (Cabua *et al.,* 2024). These plant-derived and soybean waste forms highlight the potential for sustainable materials with customized functional features, such as mechanical and nutritional, to promote eco-friendly packaging and food production. Beer bagasse, rice, and maize husks, in addition to grain and seed by-products, can improve the mechanical and physical attributes of 3DP products, including tensile strength, flexibility, and thermal stability. For example, 3D-printed beer bagasse/PLA biocomposite filaments have a tensile strength of 50MPa and a rise of 35 percent in impact resistance, ensuring packaging materials can withstand mechanical stress during handling and distribution (Carichino *et al.,* 2023; Ohaeri and Cree, 2022). Rice husk, with 20% silica, enhances stiffness and thermal stability up to 300°C, making it ideal for high-heat applications like insulation and fire-resistant building components (Morales *et al*., 2021). Wheat gluten, a valuable by-product, may be used to create 3D-printed bioplastics with 13.5 MPa tensile strength, making it ideal for biodegradable packaging that favours durability and sustainability (Alshehhi *et al*., 2024). Using tree processing by-products like oil palm fibers can enhance the mechanical strength, flexibility, and thermal stability of 3D-printed materials. Oil palm empty fruit bunch fibers, rich in lignin and cellulose, enhance tensile stress in ABS/graphene nanoplatelet composites by 29.1% and increase thermal stability to 280°C, making them ideal for electronics and automotive applications requiring heat resistance and mechanical integrity (Mohan *et al.,* 2021). The study points out the potential of tree trash to produce affordable, lightweight, and durable materials for industrial use.

Marine and Animal Processing By-Products and Waste

The materials of animal origin in the selected investigations encompass diverse by-products, including eggshells, seashells, crab and prawn shells, chitosan, salmon skin gelatin, and whey protein. These materials showcase a high amount of valuable constituents, including calcium carbonate, chitin, collagen, and proteins, which provide mechanical reinforcement, improve biocompatibility, possess antibacterial properties, and impart functional attributes such as viscoelasticity, gelling, or plasticizing effects. Seashells, including 95%–97% calcium carbonate ($CaCO_3$), when comprised into a bio-composite matrix, decreased brick weight by 40% relative to clay bricks while retaining structural stability.

PLA biocomposite, fortified with 10% eggshell particles (about 94% calcium carbonate), exhibited a markedly superior compressive strength (94.9%) compared to pure PLA while retaining a porosity of 40%, making it a viable material for bone tissue synthesis. Salmon skin by-products were employed as a gelling agent owing to their considerable collagen content (about 75%) and gelatin. Salmon skin printing material, at an appropriate concentration of 8%, was utilized to enhance gelatin flow and dimensional stability during layer-by-layer deposition by imparting shear-thinning behavior and viscoelastic qualities to the ink (Carvajal-Mena *et al.,* 2022). Other noteworthy examples include cod by-products, which is a high-quality protein, despite its minimal economic value origin. The cod by-products were converted into surimi paste using either the pH-shift method or conventional washing, and the 3DP procedure was optimized by adjusting the salt concentration and enhance the gelling properties (Gudjónsdóttir *et al.,* 2019).

The utilization of dairy by-products as ink for 3DP appears to be a relatively unexplored field of research. The food industry is the primary sector in which whey protein isolate (WPI) is used formally in 3DP particularly to take advantage on the texturing properties of whey proteins in which network structure emerges when heated in mixed gel systems. This improved gel structure, in turn enhances the integral structural properties of the printed objects, particularly their self-standing ability. Du *et al.* (2021) found that the incorporation of 20% whey proteins into a konjac flour mixed gel results in an excellent formulation for 3D printing. In contrast, the addition of 25%–30% whey proteins, although offering adequate structural support, may cause variations in the printing process if there is an insufficient balance between printing speed and extrusion rate, consequently affecting printing fidelity. Whey protein nanofibrils (WPNFs) functioned as a carrier and protective matrix for probiotic bacteria, improving their viability in 3D-printed dysphagia-friendly foods during gastrointestinal digestion (Zhang *et al.,* 2024).

By-Products from Extraction and Fermentation

Microbial fermentation and bio refinery methods can improve the nutritional, technical, and sensory qualities of food by-products. Innovative 3D-printed functional foods with high printability, mechanical stability, and fiber and antioxidant content have been produced by incorporating 6% grape pomace into dough that is prepared using broken wheat

(Jagadiswaran *et al.,* 2021). Incorporating 10% spent coffee grounds (SCGs) into low-density polyethylene (LDPE) resulted in a significant improvement of tensile strength by 20%. Additionally, incorporation of SCGs in high-density polyethylene (HDPE) composites led to an improvement in thermal stability by 10°C to 15°C, thus making these materials suitable for use in industrial packaging and heat-resistant automotive components (Romani *et al.,* 2024). Likewise, SCG improved the compressive strength of hydrogels by 25%, concurrently improving their thermal resistance, thus making them appropriate for structural and architectural applications (Choi and Yi, 2024). The development of edible systems using spent coffee grounds (SCG) will satisfy the demand for fiber-enriched functional gels or delivery mechanisms for antioxidant or bioactive compounds incorporated in 3D-printed foods. These results demonstrate the potential of reusing these by-products to yield sustainable, high-performance composites for several applications.

Biomass Processing By-Product

The utilization of biomass by-products, including flax shives and Miscanthus-derived biocarbon, has exhibited numerous advantages in 3D-printable composite formulations. Badouard *et al.* (2019) indicated that the integration of flax shives into a PLA–PBS blend at 10 wt % led to an approximate 6% increase in the Young's modulus of 3D-printed specimens while preserving satisfactory surface quality and layer adhesion. Furthermore, this new material showed better printability relative to fiber-reinforced systems, owing to better particle dispersion as well as lower porosity in the printed layers. These findings indicate that biomass by-products function as sustainable fillers while also providing mechanical and thermal improvements suitable for extrusion-based 3D printing.

Types of 3D Printing Technologies

A diverse array of 3D printing processes can be utilized to process different food by-products for the production of thermoplastics, bioplastics, biomedical scaffolds, customized foods, and building materials. The most commonly used technology is material extrusion involving extrusion of viscous and molten materials through nozzles. Under this category, methods such as fused deposition modeling, paste extrusion, direct ink writing, and laser sintering are illustrated in Fig. 2.

Fused Deposition Modelling

FDM processing requires solid filaments exhibiting low viscosity when heated and strong shear-thinning characteristics to provide smooth flow through the nozzle. Furthermore, rapid solidification during deposition is essential for preserving dimensional precision and structural integrity. The integration of food by-products into thermoplastic composites markedly improves the performance and sustainability of 3D printing materials. To effectively design materials suitable for FDM, it is essential to optimize critical process parameters, including extrusion speed, nozzle and bed temperatures, filament flowability, and nozzle diameter, to achieve the desired properties and functionalities. The analyzed research indicates that extrusion speeds ranged considerably from 20 to 50 mm/s, depending upon the materials and desired applications.

The temperature at the nozzle and on the bed surface is crucial for providing optimal layer adhesion and preventing warping. The reviewed literature typically indicated nozzle temperatures ranging from 120°C to 280°C, whereas bed temperatures ranged from ambient temperature to 100°C. Another significant printing variable is nozzle diameter, which ranges from 0.25 to 3 mm, depending on material characteristics and printing objectives. The thinnest nozzle (0.25 mm) was employed for fabricating intricate gastric floating drug delivery systems composed of PLA mixed with agro-industrial by-products (Wang *et al.,* 2024). The most prevalent nozzle diameter used in research was 0.4 mm, which provided an optimal equilibrium between precision and extrusion efficiency; this parameter was employed in various studies concerning PLA-based composites, including PLA/crab shell composites and other sustainable polymer composite material development investigations.

Conversely, larger nozzle diameters, specifically 0.5–0.6 mm, were utilized in complex formulations such as ABS/palm fiber composites and bio-carbon-enhanced composites, where structural integrity was paramount (Diederichs *et al.,* 2021; Marton *et al.* 2022). In large-scale applications, including the production of PLA/corncob composites and fluorescent bio-composites, a 0.8-mm nozzle was employed to enhance printing speed and improve material flow (Mayer Laigle *et al.,* 2021; Ohaeri and Cree, 2022).

Direct Ink Writing

DIW employs extrusion-based deposition with more fluid materials, such as gels or slurries, requiring post-processing, such as curing or drying, to ascertain structural integrity. Various food by-products such as orange peels, okra, and durian husks have been researched as materials to improve the functionality of

3D-printed foods and other non-edible materials. For this purpose, specialized inks have been investigated, such as electromagnetic interference (EMI) shielding, thermally tunable biocomposite inks, and biomass-derived bioplastics for multiproduct biorefineries. Innovative applications such as non-fluid agar gel-based inks for 3D-printed mycelium structures as potential self-healing materials. Electro-conductive inks derived from chitosan were utilized for electromagnetic interference shielding and strain-sensing applications. The ink formulation including 66.7% carbon fibers (CF) enhanced electrical conductivity, tensile strength (20.8 MPa), and Young's modulus (3.92 GPa), indicating that the material can preserve structural integrity while functioning as an optimal conductor (Sanandiya *et al.* 2024).

Table 1 : Classified applications of 3D printing using food by-products, sorted by types (Source: Bareen *et al.,* 2025).

Food waste category	3D printed product	Food material	Combined matrix with percentage (wt.%) used	References
Plant-derived product processing	3D-printed edible food for dysphagia	Spinach stems and kale stalks	Spinach and kale purees with potato and corn starch (50 %)	Pant *et al.* (2023)
	Unique and appealing snacks	Imperfect broccoli and carrots	Broccoli and carrot powders with wheat flour, olive oil, and salt (25-75 %)	Ahmadzadeh *et al.* (2024)
	Photo curable formulation for VAT printing	Aloe vera peel	Microcrystalline cellulose with fish skin gelatin, polyethylene glycol diacrylate, sodium carbonate, hydrochloric acid and allylamine (5-33 %)	Cabua *et al.* (2024)
	3D printed noodles	Potato peel	Whole wheat flour and potato peel powder (40 %)	Muthurajan *et al.* (2021)
	Biocomposite filaments	Tomato stem	PLA with tomato stem powder and Joncryl (5-10 %)	Pemas *et al.* (2024)
	Bioflavonoid-rich snacks	Orange peel	Rheology-modified inks containing orange peel waste, with additives for enhanced printability	Leo *et al.,* (2022)
	Fiber-enriched apricot gel snacks	Orange by-products	Gelatin gels with apricot pulp (30-70%) and orange by-products, freeze-dried (3.5-5.8 %)	Molina-Montero *et al.* (2023)
	Bioactive rich snacks	Orange peel	Orange peel powder with xanthan gum (20 %)	Da Tan *et al.* (2023)
	Biodegradable food packaging casings	Banana peel	Banana peel powder with 1% (w/w) guar gum (99 %)	Nida *et al.* (2023)
	Natural filler composite filaments	Cocoa bean shells	Recycled polypropylene with 5 wt% cocoa bean shell particles (5 %)	Morales *et al.* (2021)
	3D-printed biodegradable food packaging	Banana peel and sugarcane bagasse	Mixture of banana peel and sugarcane bagasse (Greater than 99 %)	Nida *et al.* (2022)
	Biocomposite filaments	Hydroxypropyl methylcellulose (HPMC) derived from mixed vegetable waste	PLA with HPMC	Jiang *et al.* (2020)
	Natural fiber composite filaments	Rice husk	Recycled polypropylene with rice husk (5-10%)	Morales *et al.* (2021a)
	Corn starch and cellulose fibers composites for the medical and food applications	Corn husks (cellulose fibers extracted)	Cellulose fibers from corn husks, corn starch (10%)	Islam and Jiang (2022)
	Biocomposite filaments	Buckwheat husk	Buckwheat husk and polylactic acid and thermoplastic starch	Andrzejewski *et al.* (2021)
Marine and Animal Processing	Biomedical scaffolds utilize hydrogels	Chitosan from crustacean shells	Chitosan/hyaluronic acid polyelectrolyte complex (20%)	Braccini *et al.* (2024)
	Chitin-based architecture for tissue engineering	Crayfish shells	Chitin extracted from crayfish shells, acrylic acid, polyethylene glycol diacrylate, and photo initiator (6%)	Li *et al.* (2023)
	Biocomposite filament	Crab shell	Polylactic acid mixed with 7% crab shell	Palaniyappan *et*

			particles	*al.* (2024)
	Biocomposite material for bone tissue engineering	Crab shell powder	Crab shell powder incorporated into lactic acid (1.5%)	Yang *et al.* (2023)
	Electroconductive ink for strain sensing applications	Prawn shells	Chitosan mixed with carbon fibers and silk fibroin (27%)	Sanandiya *et al.* (2024)
	Salmon skin gells	Salmon skin	Salmon skin gelatin gelled at various concentrations (2-14%)	Carvajal-Mena *et al.* (2022)
	3D printed surimi	Cod by-products	Surimi made from cod by-products (greater than 99%)	Gudjónsdóttir *et al.* (2019)
	Ribose-crosslinked gelatin products	Gelatin	Gelatin, crosslinked ribose and glycerol (2.5-5%)	Stevenson *et al.* (2019)
	Cheddar cheese	Whey protein isolate (WPI)	Reduced-fat processed cheese and WPI nanofibrils (less than 40 %)	Wang *et al.* (2023)
	Konjac hybrid gel	Whey protein powder (WP)	Konjac flour, WP, and sodium bicarbonate (5-30%)	Du *et al.* (2021)
	Scaffolds for wound dressing applications	Whey Protein Concentrate (WPC)	Poly lactic acid, WPC, Dimethylformamide and Dichloromethane (25- 50 %)	Kayadurmus *et al.* (2024)
By-products from Extraction and Fermentation	Functional cookies	Grape pomace	Wheat flour was replaced with 4%, 6%, and 8% grape pomace	Jagadiswaran *et al.* (2021)
	Coloured bio composite filaments	Spent coffee grounds (SCGs)	PLA with micro/nano-structured decolorized spent coffee grounds (MN-DSCGs) (2-20%)	Li *et al.* (2021)
	Cellulose/ soy protein-based hydrogels	Cellulose-containing residues from agar production	Soy protein isolate, agar residue, porcine gelatin, and glycerol (less than 8 %)	Uranga *et al.* (2023)
	Edible soy protein films	Grape seed, green tea	Soy protein isolate with grape seed extract or green tea extract (1-5%)	Ahmadzadeh *et al.* (2023)
	Biomass/PLA composite filaments	Spent coffee grounds and spent tea leaves	PLA with spent coffee grounds and spent tea leaves (40%)	Yu and Wong (2023)
Biomass	Biomass–fungi composites	Biomass	Biomass fungi mix, wheat flour, and psyllium husk powder (50 %)	Rahman *et al.* (2022)
	Biodegradable biocomposite filaments	Flax shives	Flax shives mixed with PLLA, PLLA/PBS, and PBAT matrices (10 - 30%)	Badouard *et al.* (2019)
	Biocomposite filaments	*Miscanthus* biocarbon	Poly (trimethylene terephthalate) with *Miscanthus* biocarbon (5-10%)	Diederichs *et al.* (2021)

Paste Extrusion

Paste extrusion, which includes semi-solid extrusion (SSE) and hot melt extrusion (HME), has been extensively employed for the upcycling of food waste materials. Semi-solid extrusion contains the extrusion of semi-solid materials such as paste, gels, or other high-viscosity substances, typically using mechanical force applied via a piston, screw, or pneumatic pressure. Overall, 3D printing conditions for semi-solid extrusion consist of ambient to moderate temperatures under pneumatic or screw pressures of 0.05-0.60 MPa, whereas hot melt extrusion operates at melt temperatures of 100°C-140°C with the melt conveyed under comparable mechanical pressures. SSE was utilized to produce oral films for custom-formulated medications with carboxymethyl cellulose (CMC) sourced from durian rind waste (Panraksa *et al.,* 2023). This method facilitated the acquisition of programmable drug release profiles by the alteration of printing parameters, including infill density and pattern design. For this purpose, grid-patterned films showed more porosity, resulting in faster drug release. These studies collectively highlight the versatility of paste extrusion methods for enhancing sustainability and functionality across several sectors. By recycling food by-products into high-performance materials for construction, packaging, and biomedical uses, these inventions offer sustainable solutions appropriate to large-scale adoption. Another known important aspect is the type of food material suitable for 3D printing.

Ingredient-based methods recognize food inks into five major classes, such as confectionary inks, milk-based dairy inks, chocolate or doughs, edible hydrogels, and inks prepared from plant or animal sources. Furthermore, depending on the viscoelastic properties of the inks, they are classified as natively and non-natively extrudable food inks. Natively extrudable inks possess advantageous viscoelastic qualities, enabling direct extrusion without the incorporation of any binders. Conversely, non-natively extrudable food inks necessitate an appropriate binder to provide smooth extrusion and print stability. Mostly used food inks are as follows:

Sugar

Sugar, in the form of granules or powder, is used in stereolithography, hot air sintering, and laser binding. It is heated to the temperature of 160-180 °C to melt and fuse end-to-end particles. The heat source applied over the powder bed disrupts powder flowability and results in pattern building.

Gelatin

Gelatin has a distinct "melt-in-the-mouth" texture that delivers a significant mouthfeel, thus making it amongst the most desirable substrate for 3D food printing. Gelatin, upon hydration forms a single random coil, which upon gelation forms a triple helix structure. During this process, tiny polypeptide chains form at intersections, retracting the triple helix structure.

Wheat flour

The wheat flour dough with suitable consistency is used in 3D food printing, followed by baking or frying. The flowability of dough and strength of structure is adjusted by adding butter and egg yolk, respectively.

Chocolate

Fine cocoa powder can either directly be used in a hot melt extrusion process or a suitable slurry can be prepared using butter and additives like magnesium stearate to extrude in the cold extrusion method. These additives can boost the nutritive profile of the printed food. Moreover, it may also reduce slippage in screw extruders.

Dairy products

Whey protein isolates are reported as a good additive that increases the protein content of the substrate as well as improves the printing performance. Skim milk powder also yields excellent printability due to its lower fat content as compared to milk powders. Other additives like butter and cheese determine the flowability of food inks when added in suitable quantities with substrate.

Hydrogels

Hydrogels, or hydrocolloids, are generally blended with flavour concentrates and added to the substrates, which helps in better binding and smooth flowability. By the use of hydrogels, the textural variations in food inks can be achieved as per our desirability.

Laser Sintering

Laser sintering technology demonstrates significant potential for the fabrication of 3D-printed structures from food by-products. This employs a high-powered laser to sinter powdered materials, combining them to produce solid structures. In this, the unsintered powder serves as an inherent support for the component during fabrication, facilitating the formation of complex shapes by accurately directing the laser to sinter exclusively the specified regions of the powder bed. Scan speed, laser power, and thickness of layer are the critical factors influencing on the sintering process. Previous research has investigated the use of various biomass derivatives such as rice husk, bamboo, walnut shell powder, and pine wood as feedstock to produce sustainable biocomposites using laser sintering. In laser sintering, particle size plays the major role contributing to its ranges, such as smaller, medium, and larger, affected on internal density and porosity (Yu *et al.,* 2021). This study shows that smaller particle sizes (≤ 58 µm) caused particle aggregation and insufficient material to occupy gaps during the sintering process, leading to rough surfaces. In contrast, particle sizes in the medium range (e.g., 80–120 µm) produce smoother surfaces due to enhanced packing efficiency, whereas larger particles that do not pack effectively lead to the creation of voids and elevated internal porosity, which may not necessarily elevate surface roughness but negatively impacts density and mechanical integrity. Larger particles may be unevenly distributed on the surface, increasing roughness when the size difference is severe. These composites were characterized by high dimensional accuracy and excellent biodegradability, making them ideal for fields such as biomedical devices and food packaging (Colucci *et al.* 2024).

Role of 3D Printed Food Waste Materials in Attaining Circular Economy Goals and Global Sustainability Initiatives

The 3D printing of food by-products is essential for attaining circular economy objectives by creating a closed-loop system of six interconnected stages. The cycle begins with collecting food by-products including banana peels, walnut shells, and rice husks, which usually get tossed or underutilized. Waste is recovered and upcycled to extract useful nutrients and materials such as proteins, cellulose, and antioxidants for further use. Extracted components are employed in 3DP inks to create niche materials such as biocomposite filaments and edible gels. By combining upcycled components into 3DP (FDM, paste extrusion, and SLS), inks can be transformed into sustainable goods like biodegradable packaging, functional foods, biomedical scaffolds, and biocomposite bricks. The end products and advantages showcase different uses that reduce virgin resource consumption. Post-consumer methods of processing including composting, anaerobic digestion, and pyrolysis, enable recycling or repurposing of end-of-life materials, completing the circular flow. This step recovers nutrients and regenerates materials, feeding back into the first by-product collection stage. Integrating food by-product 3DP stages corresponds with CE principles, reshaping consumption and production patterns for sustainable reuse, waste reduction, and resource cycle closure (Fig. 3).

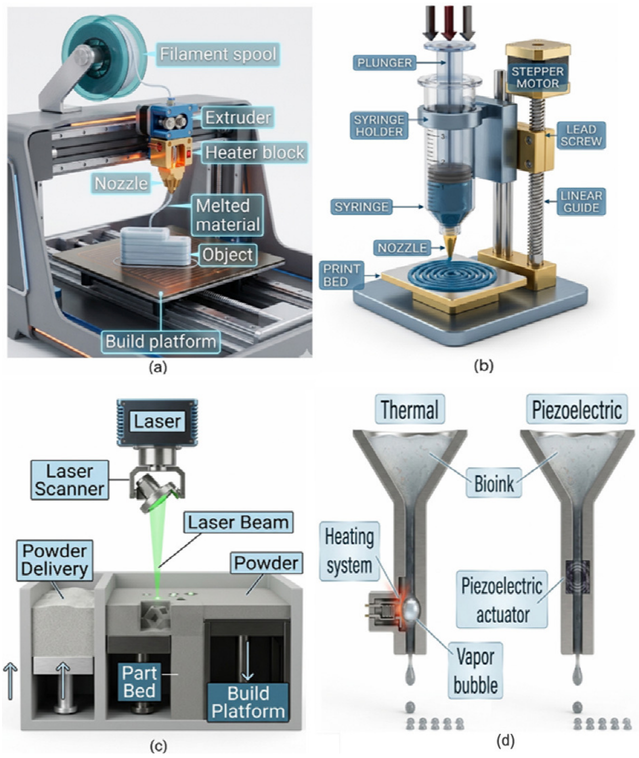

Fig. 2 : Schematic illustration of commonly employed 3D printing techniques (a) Fused deposition modelling (b) extrusion-based 3D printing using a syringe-based system (c) Laser sintering (d) Direct Inkjet printing

Reduced Emission in Post-Consumer Processing

The utilization of food by-products in 3D printing has the advantage of energy recovery with reduced carbon emissions. The carbon-neutral characteristic of food by-product recovery is rooted in the principle that the carbon released during decomposition or energy recovery was initially sequestered by plants during their growth. This stands in direct contrast to man-made materials such as plastics, which emit considerable quantities of CO_2 and other pollutants upon incineration. This analysis highlights the extensive variety of food by-products that can be recycled into beneficial food products. SCG/PLA 3D-printed composites exhibited superior thermal stability (by 10°C–15°C) compared to pure PLA, rendering them appropriate for energy recovery applications post-product lifespan (Romani *et al.,* 2024). Likewise, rice husk/PLA composites can endure temperatures above 300°C, rendering them suitable for high-temperature applications such as fire-resistant construction materials (Morales *et al.,* 2021). These materials can subsequently be converted into biofuel without generating harmful emissions.

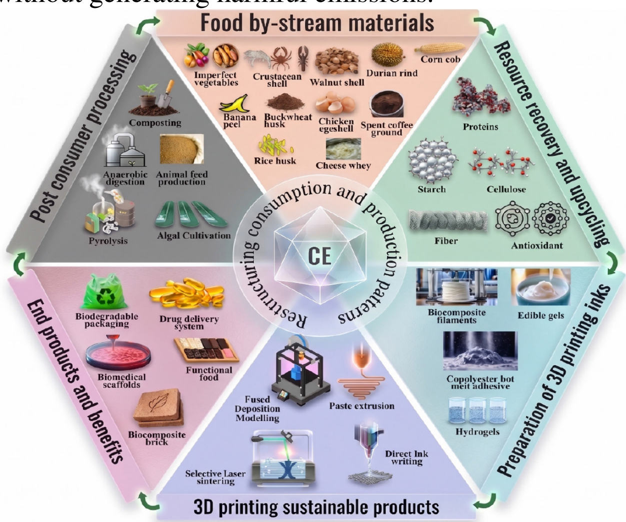

Fig. 3 : Framework for a circular economy integrating 3D printing with food by-products

Localized Upcycling of Perishable Food Waste for On-Demand Production

Untreated perishable food waste poses a distinct concern due to its rapid breakdown and methane emissions. Industry can reduce emissions by incorporating food by-products into local 3DP, reducing transit and centralized waste processing. Using perishable trash like vegetable stalks, fruit peels, and fish bones at their creation site is a huge advancement in 3D-printing locally. Research suggests that using OPW to manufacture biodegradable packaging can lessen the environmental impact of food waste and plastic packaging (Leo *et al.,* 2022; Molina-Montero *et al.,* 2023). According to Scaffaro *et al.* (2022), fish bone waste can be used to produce biocomposites for biomedical purposes, using its calcium carbonate content to create resilient, biodegradable materials. This article demonstrates how local 3DP can transform food waste into essentials, decreasing carbon emissions and preventing methane emissions from waste degradation.

Nutrient-rich, Customized Foods for Sustainable Food Production

3DP enables the creation of customized nutrient-dense food items from food by-products, promoting sustainable food production. By converting waste materials like okara or grape pomace into 3D-printed snacks, the food industry can cut waste while offering nutritious foods. Okara 3D-printed foods can contain 33% okara and 28% protein, improving their nutritional value (Lee *et al.,* 2021). Grape pomace-enriched 3D-printed cookies increased antioxidant and fiber content by up to 8% (Jagadiswaran *et al*. 2021). Using food industry by-products in 3D-printed foods can redirect significant amounts of waste material. Using waste-derived inks can minimize food-waste disposal by 20-30% compared to standard processing methods, according to a techno-economic study (Yu and Wong, 2023). Converting food waste into printed materials can reduce waste volumes by 40-60% (Pant *et al*., 2023). Research suggests that food waste might be transformed into nutritious, customized products, enhancing sustainability.

Impact of 3D Printed Food Waste Materials on Global Sustainability Objectives

The incorporation of FBS materials into 3DFP presents an innovative method for advancing many global sustainability goals, especially those specified in the United Nations Sustainable Development Goals. This technique directly supports SDG 12 (Responsible Consumption and Production) by converting nutrient-rich wastes, such as fruit pomace, vegetable peels, and cereal bran, into printable food matrices, thus encouraging waste valorization and reducing resource loss in the agri-food chain. It also advances SDG 2 (Zero Hunger) by developing customizable, nutrient-enriched foods suited for malnourished or at-risk groups, particularly when combined with individualized nutrition practices. Furthermore, decentralized production combined with 3DFP reduces food miles and refrigeration demands, so conforming to SDG 13 (Climate Action) by reducing emissions linked to traditional food processing and transportation. This application of 3D printing, however still developing, symbolizes a shift towards circular, resilient food systems that integrate environmental stewardship with nutritional innovation. Enhanced integration with regulatory frameworks and life-cycle indicators will be essential to magnify its influence within overall sustainability initiatives.

Nutrient stability and shelf life considerations

Early research shows that extrusion-based 3DFP, operating at mild temperatures (20-60°C), minimizes thermal stress on sensitive micronutrients, allowing them to survive the printing process. DPPH AC was reduced by 12% in strawberry-based snacks printed with 10%-20% starch over seven days at ambient temperature, indicating partial loss of free-radical scavenging ability, even under mild settings (Bebek Markovinović *et al*. 2023). A study by Severini *et al.* (2018) found that 3D-printed fruit-vegetable snacks stored at 5°C under modified atmosphere lost ~30% antioxidant activity and ~44% TPC after 8 days, suggesting that cold storage alone is insufficient to preserve polyphenolic compounds in newly formed matrices. Zhou *et al.* (2023) found that gellan gels enriched with *Aronia melanocarpa* (black chokeberry) remained structurally intact after 14 days at 4°C. However, anthocyanin and polyphenol levels were not measured during the procedure. Although orange-byproduct-fortified apricot gels showed increased rheological strength, there was no evidence on flavanone stability following freeze-drying and storage (Molina-Montero *et al.,* 2023). The main mechanisms of nutritional division in 3D-printed structures are oxygen diffusion, light-induced oxidation, and water-mediated hydrolysis or Maillard reactions. Lipid- or protein-based microencapsulation, antioxidant co-formulation, and low-water-activity post-print drying are promising mitigating techniques, although further kinetic confirmation is needed. Nutritionally exact, stable 3D-printed foods cannot be achieved without defined shelf-life techniques that evaluate nutrient kinetics across major vitamin, mineral, and bioactive classes.

Conclusion

Integrating food by-products and waste into biocomposite materials for non-food applications may boost printability, mechanical properties, antibacterial properties, and carbon emissions. Examples include beer bagasse, corn, and rice husk in PLA filaments; increased tensile strength in copolyester enriched with nut waste; and a biomedical scaffold made of PLA/crab shell composite. Combining by-products with other ingredients might enhance crucial aspects of food inks, including viscosity, shear-thinning behavior, texture, and mechanical integrity, for 3DP applications. Utilizing fibers, proteins, carbohydrates, and bioactives from broccoli, GS, potato peel, and salmon skin can considerably improve the qualities of food inks.

Incorporating by-products can boost the nutritional value of 3D-printed food by up to 22% of micronutrients (e.g., grape pomace in cookies) and 45% of proteins (e.g., okara in snacks). Additionally, sensory qualities can be expanded by altering color, texture, taste, and aroma. Data suggests that 3D printing with FBS material can reduce waste/by-product disposal volumes by 20% or more, while providing nutrient-fortified foods. Utilizing recycled streams allows for custom, nutritious, and sustainable food choices.

References

Ahmadzadeh, S., Hettiarachchy, N., Luthra, K. *et al*. (2023). Effects of polyphenol-rich grape seed and green tea extracts on the physicochemical properties of 3D-printed edible soy protein films. *Food Packaging and Shelf Life*, **40**, 101184.

Ahmadzadeh, S., Clary, T., Rosales, A. and Ubeyitogullari, A. (2024). Upcycling imperfect broccoli and carrots into healthy snacks using an innovative 3D food printing approach. *Food Science and Nutrition*, **12**(1), 84–93.

Alami, A. H., Olabi, A. G., Khuri, S., Aljaghoub, H., Alasad, S., Ramadan, M. and Abdelkareem, M. A. (2024). 3D printing in the food industry: Recent progress and role in achieving sustainable development goals. *Ain Shams Engineering Journal*, **15**(2), 102386.

Alshehhi, J. R. M. H., Wanasingha, N., Balu, R., *et al*. (2024). 3D-printable sustainable bioplastics from gluten and keratin. *Gels*, **10**(2), 136.

Andrzejewski, J., Grad, K., Wisniewski, W. and Szulc, J. (2021). The use of agricultural waste in the modification of poly(lactic acid)-based composites intended for 3D printing applications: The use of toughened blend systems to improve mechanical properties. *Journal of Composites Science*, **5**(10), 253.

Badouard, C., Traon, F., Denoual, C., Mayer-Laigle, C., Paës, G. and Bourmaud, A. (2019). Exploring mechanical properties of fully compostable flax reinforced composite filaments for 3D printing applications. *Industrial Crops and Products*, **135**, 246–250.

Bebek Markovinović, A., Putnik, P., Bosiljkov, T., *et al*. (2023). 3D printing of functional strawberry snacks: Food design, texture, antioxidant bioactive compounds, and microbial stability. *Antioxidants*, **12**(2), 436.

Braccini, S., Chen, C.-B., Łucejko, J. J., *et al*. (2024). Additive manufacturing of wet-spun chitosan/hyaluronic acid scaffolds for biomedical applications. *Carbohydrate Polymers*, **329**, 121788.

Cabua, M. C., Piras, M. V., Dessi, D., *et al*. (2024). Microcrystalline cellulose from aloe plant waste as a platform for green materials: Preparation, chemical functionalization, and application in 3D printing. *ACS Applied Polymer Materials*, **6**(12), 6926–6936.

Carichino, S., Scanferla, D., Fico, D., *et al*. (2023). Poly-lactic acid-bagasse-based biocomposite for additive manufacturing. *Polymers*, **15**(21), 1–21.

Carvajal-Mena, N., Tabilo-Munizaga, G., Pérez-Won, M. and Lemus Mondaca, R. (2022). Valorization of salmon industry by-products: Evaluation of salmon skin gelatin as a biomaterial suitable for 3D food printing. *LWT*, **155**, 112931.

Choi, H.-I. and Yi, H. (2024). Biofabrication in architecture: 3D bioprinting of nature-sourced multi-material powder hydrogels, material testing, and prototyping. *Journal of Building Engineering*, **87**, 109122.

Colucci, G., Lupone, F., Bondioli, F. and Messori, M. (2024). 3D printing of PBAT-based composites filled with agro-wastes via selective laser sintering. *European Polymer Journal*, **215**, 113197.

Da Tan, J., Lee, C. P. and Foo, S. Y. (2023). 3D printability and biochemical analysis of revalorized orange peel waste. *International Journal of Bioprinting*, **9**(5), 776.

Diederichs, E., Picard, M., Chang, B. P., Misra, M. and Mohanty, A. (2021). Extrusion based 3D printing of sustainable biocomposites from biocarbon and poly(trimethylene terephthalate). *Molecules*, **26**(14), 4164.

Du, Y., Zhang, M. and Chen, H. (2021). Effect of whey protein on the 3D printing performance of konjac hybrid gel. *LWT*, **140**, 110716.

Gudjónsdóttir, M., Napitupulu, R. J. and Kristinsson, H. T. P. (2019). Low field NMR for quality monitoring of 3D printed surimi from cod by-products: Effects of the pH-shift method compared with conventional washing. *Magnetic Resonance in Chemistry*, **57**(9), 638–648.

Islam, M. N. and Jiang, Y. (2022). 3D printable sustainable composites with thermally tunable properties entirely from corn-based products. *ACS Sustainable Chemistry & Engineering*, **10**(24), 7818–7824.

Jagadiswaran, B., Alagarasan, V., Palanivelu, P., Theagarajan, R., Moses, J. A. and Anandharamakrishnan, C. (2021). Valorization of food industry waste and by-products using 3D printing: A study on the development of value-added functional cookies. *Future Foods*, **4**, 100036.

Jiang, G., Yang, T., Xu, J., *et al*. (2020). Investigation into hydroxypropyl methylcellulose-reinforced polylactide composites for fused deposition modelling. *Industrial Crops and Products*, **146**, 112174.

Kayadurmus, H. M., Rezaei, A., Ilhan, E., *et al*. (2024). Whey protein loaded 3D-printed poly(lactic) acid scaffolds for wound dressing applications. *Biomedical Materials*, **19**(4), 045045.

Lee, C. P., Takahashi, M., Arai, S., Lee, C.-L. K. and Hashimoto, M. (2021). 3D printing of okara ink: The effect of particle size on the printability. *ACS Food Science & Technology*, **1**(11), 2053–2061.

Leo, C. H., Lee, C. P. and Foo, S. Y. (2022). 3D printed nutritious snacks from orange peel waste. *Materials Today: Proceedings*, **70**, 12–16.

Li, S., Shi, C., Sun, S., *et al*. (2021). From brown to colored: Polylactic acid composite with micro/nano-structured white spent coffee grounds for three-dimensional printing. *International Journal of Biological Macromolecules*, **174**, 300–308.

Li, Z., Li, M.-C., Liu, C., *et al*. (2023). Microwave-assisted deep eutectic solvent extraction of chitin from crayfish shell wastes for 3D printable inks. *Industrial Crops and Products*, **194**, 116325.

Liu, Z., Zhang, M., Bhandari, B. and Wang, Y. (2017). 3D printing: Printing precision and application in food sector. *Trends in Food Science & Technology*, **69**, 83–94.

Marton, A. M. S., Monticeli, F. M., Zanini, N. C., *et al*. (2022). Revalorization of Australian royal palm (*Archontophoenix* *alexandrae*) waste as reinforcement in acrylonitrile butadiene styrene (ABS) for use in 3D printing pen. *Journal of Cleaner Production*, **365**, 132808.

Mayer-Laigle, C., Foulon, L., Denoual, C., *et al*. (2021). Flax shives-PBAT processing into 3D printed fluorescent materials with potential sensor functionalities. *Industrial Crops and Products*, **167**, 113482.

Bareen, M. A., Antonio, D., Corradini, M. G., Caporizzi, R., D'Incecco, P., Sindaco, M. and Severini, C. (2025). Enhancing 3D printing performance and product quality through the valorization of food by-products and waste. *Comprehensive Reviews in Food Science and Food Safety*, **24**, e70267.

Mohan, D., Bakir, A. N., Sajab, M. S., *et al*. (2021). Homogeneous distribution of lignin/graphene fillers with enhanced interlayer adhesion for 3D printing filament. *Polymer Composites*, **42**(5), 2408–2421.

Molina-Montero, C., Vicente-Jurado, D., Igual, M., Martínez-Monzó, J. and García-Segovia, P. (2023). Fiber enrichment of 3D printed apricot gel snacks with orange by-products. *Gels*, **9**(7), 569.

Morales, M. A., Maranon, A., Hernandez, C. and Porras, A. (2021). Development and characterization of a 3D printed cocoa bean shell filled recycled polypropylene for sustainable composites. *Polymers*, **13**(18), 3162.

Morales, M. A., Atencio Martinez, C. L., Maranon, A., Hernandez, C., Michaud, V. and Porras, A. (2021). Development and characterization of rice husk and recycled polypropylene composite filaments for 3D printing. *Polymers*, **13**(7), 1067.

Muthurajan, M., Veeramani, A., Rahul, T., Gupta, R. K., Anukiruthika, T., Moses, J. A. and Anandharamakrishnan, C. (2021). Valorization of food industry waste streams using 3D food printing: A study on noodles prepared from potato peel waste. *Food and Bioprocess Technology*, **14**(10), 1817–1834.

Nida, S., Moses, J. A. and Anandharamakrishnan, C. (2022). 3D extrusion printability of sugarcane bagasse blended with banana peel for prospective food packaging applications. *Sugar Tech*, **24**(3), 764–778.

Ohaeri, O. and Cree, D. (2022). Development and characterization of PHB-PLA/corncob composite for fused filament fabrication. *Journal of Composites Science*, **6**(9), 249.

Palaniyappan, S., Sivakumar, N. K. and Sekar, V. (2024). Sustainable approach to the revalorization of crab shell waste in polymeric filament extrusion for 3D printing applications. *Biomass Conversion and Biorefinery*, **14**(14), 15721–15738.

Panraksa, P., Rachtanapun, P., Thipchai, P., *et al*. (2023). Sustainable 3D printing of oral films with tunable characteristics using CMC-based inks from durian rind wastes. *European Journal of Pharmaceutics and Biopharmaceutics*, **186**, 30–42.

Pant, A., Ni Leam, P. X., Chua, C. K. and Tan, U. X. (2023). Valorisation of vegetable food waste utilising three-dimensional food printing. *Virtual and Physical Prototyping*, **18**(1), e2146593.

Pemas, S., Gkiliopoulos, D., Samiotaki, C., Bikiaris, D. N., Terzopoulou, Z. and Pechlivani, E. M. (2024). Valorization of tomato agricultural waste for 3D-printed polymer composites based on poly(lactic acid). *Polymers*, **16**(11), 536.

Rahman, A. M., Bhardwaj, A., Pei, Z., Ufodike, C. and Castell-Perez, E. (2022). The 3D printing of biomass–fungi composites: Effects of waiting time after mixture preparation on mechanical properties, rheological properties, minimum extrusion pressure, and print quality of the prepared mixture. *Journal of Composites Science*, **6**(8), 237.

Rahman, A. M., Rahman, T. T., Pei, Z., Ufodike, C. O., Lee, J. and Elwany, A. (2023). Additive manufacturing using agriculturally derived biowastes: A systematic literature review. *Bioengineering*, **10**(7), 845.

Rayna, T. and Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. *Technological Forecasting and Social Change*, **102**, 214–224.

Romani, A., Paramatti, M., Gallo, L. and Levi, M. (2024). Large-format material extrusion additive manufacturing of PLA, LDPE, and HDPE compound feedstock with spent coffee grounds. *International Journal of Advanced Manufacturing Technology*, **134**(3–4), 1–17.

Sanandiya, N. D., Pai, A. R., Seyedin, S., Tang, F., Thomas, S. and Xie, F. (2024). Chitosan-based electroconductive inks without chemical reaction for cost-effective and versatile 3D printing for electromagnetic interference (EMI) shielding and strain-sensing applications. *Carbohydrate Polymers*, **337**, 122161.

Scaffaro, R., Gulino, E. F. and Citarrella, M. C. (2024). Multifunctional 3D-printed composites based on biopolymeric matrices and tomato plant (*Solanum lycopersicum*) waste for contextual fertilizer release and Cu(II) ions removal. *Advanced Composites and Hybrid Materials*, **7**(3), 95.

Severini, C. and Derossi, A. (2016). Could the 3D printing technology be a useful strategy to obtain customized nutrition? *Journal of Clinical Gastroenterology*, **50**, S175–S178.

Severini, C., Derossi, A., Ricci, I., Caporizzi, R. and Fiore, A. (2018). Printing a blend of fruit and vegetables: New advances on critical variables and shelf life of 3D edible objects. *Journal of Food Engineering*, **220**, 89–100.

Stevenson, M., Long, J., Guerrero, P., de la Caba, K., Seyfoddin, A. and Etxabide, A. (2019). Development and characterization of ribose-crosslinked gelatin products prepared by indirect 3D printing. *Food Hydrocolloids*, **96**, 65–71.

Tian, J., Bryksa, B. C. and Yada, R. Y. (2016). Feeding the world into the future–food and nutrition security: The role of food science and technology. *Frontiers in Life Science*, **9**(3), 155–166.

Tyupova, A. and Harasym, J. (2024). Valorization of fruit and vegetables industry by-streams for 3D printing—A review. *Foods*, **13**(14), 2186.

Uranga, J., Carranza, T., Peñalba, M., de la Caba, K. and Guerrero, P. (2023). Valorization of agar production residue as a filler in soy protein hydrogels for 3D printing. *International Journal of Bioprinting*, **9**(4), 731.

Varvara, R. A., Szabo, K. and Vodnar, D. C. (2021). 3D food printing: Principles of obtaining digitally-designed nourishment. *Nutrients*, **13**(10), 3617.

Wang, D., Guo, J., Wang, Y., *et al*. (2023). Whey protein isolate nanofibrils as emulsifying agent to improve printability of cheddar cheese for 3D printing. *Food Hydrocolloids*, **142**, 108807.

Wang, L., Yong, L. X. and Loo, S. C. J. (2024). Utilizing food waste in 3D-printed PLA formulations to achieve sustainable and customizable controlled delivery systems. *ACS Omega*, **9**(31), 34140–34150.

Wong, G. H. C., Pant, A., Zhang, Y., Chua, C. K., Hashimoto, M., Leo, C. H. and Tan, U. X. (2022). 3D food printing–sustainability through food waste upcycling. *Materials Today: Proceedings*, **70**, 627–630.

Yang, F., Ye, X., Zhong, J., *et al*. (2023). Recycling of waste crab shells into reinforced poly(lactic acid) biocomposites for 3D printing. *International Journal of Biological Macromolecules*, **234**, 122974.

Yoha, K. S. and Moses, J. A. (2023). 3D printing approach to valorization of agri-food processing waste streams. *Foods*, **12**(1), 212.

Yu, I. K. M. and Wong, K. H. (2023). Food waste-derived 3D printable materials: A carbon neutral solution to global food loss. *Trends in Food Science and Technology*, **137**, 156–166.

Yu, Y., Jiang, M., Wang, S., *et al*. (2021). Impact of particle size on performance of selective laser sintering walnut shell/co-PES powder. *Materials*, **14**(2), 1–14.

Zhang, Y., Wang, Y., Dai, X., *et al*. (2024). Biointerfacial supramolecular self-assembly of whey protein isolate nanofibrils on probiotic surface to enhance survival and application to 3D printing dysphagia foods. *Food Chemistry*, **460**(P3), 140720.

Zhou, Q., Nan, X., Zhang, S., *et al*. (2023). Effect of 3D food printing processing on polyphenol system of loaded *Aronia melanocarpa* and post-processing evaluation of 3D printing products. *Foods*, **12**(10), 2068.