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3D printing technology for valorization of food processing wastes and byproducts: A systematic review

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ABSTRACT

It is estimated that over 1.3 billion tons of waste are generated annually from food processing, which poses significant environmental and economic challenges. This review delineates the potential of 3D printing technology in valorizing food waste and explores an achievable reduction of 40–60 % in waste disposal through product innovation. This method allows nutrient-rich waste materials like fruit peels, vegetable waste, shellfish shells, and cereal byproducts to be converted into edible and biodegradable packaging aligned with circular economy principles and sustainable food systems. Advances in 3D printing parameters, including optimized extrusion temperature and nozzle diameter, have been shown to improve efficiency by up to 30 % and the quality and integrity of the final product. Such applications are fiber-enriched snack foods and protein-enriched products with 20–35 % nutrient increases, along with biodegradable packaging that breaks down 50 % faster than conventional plastic. Case studies reveal that implementing such solutions by food manufacturers can generate as much as 25 % savings in waste management costs. These advancements are, however, challenged, especially concerning material variability, printability, and regulatory compliance. Existing studies have primarily focused on material formulation and extrusion properties, but gaps persist in large-scale implementation, standardization, and economic feasibility. Future research should emphasize AI-driven optimization to enhance printability by 15–20 %, explore novel biopolymer blends for improved mechanical properties, and integrate blockchain for enhanced traceability and transparency in waste valorization. A comprehensive understanding of the history of the development of the field and the issues it has not solved is important in accelerating the implementation of 3D printing in sustainable food waste management. This study concludes that 3D printing is a transformative approach to reducing food waste and advancing sustainability in the food and packaging sectors.

Introduction

Food loss and waste are global issues, with agri-food processing waste streams being a significant concern. Food waste, defined as food and inedible parts removed from the human food supply chain, affects the environment, economy, and society (Girotto et al., 2015; Papargyropoulou et al., 2014). Nearly one-third of all food produced ends up being wasted, resulting in 1.3 billion tons of food annually (Pleissner & Lin, 2013). Countries like Egypt, Pakistan, Sri Lanka, and Iraq have the highest food waste levels, indicating inefficiencies in their consumption and waste management systems. Moderate levels are observed in countries like China, Kenya, Ethiopia, and India, suggesting room for improvement. Countries like Bangladesh, Afghanistan, and Syria have lower food waste estimates, often below 200 kg/capita/year, indicating limited food availability, efficient consumption, or lower income levels impacting overall food production and waste (Fig. 1). Food waste occurs at various levels within the food supply chain, including production, processing, distribution, and consumption (Raak et al., 2017). Such losses not only waste resources like water, energy, and labor but also contribute significantly to greenhouse gas emissions, worsening climate change. Addressing this issue is crucial for achieving sustainable development goals and building a more resilient global food system.

Food waste and the circular economy

In response to the critical need for waste reduction, the idea of a circular economy has picked up steam. In contrast to the traditional linear economic model of “take, make, and dispose,” the circular

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economy is one that focuses on being efficient with resources, minimizing waste, and using resources continuously (Pal et al., 2024). This approach, within the context of food systems, is the recovery and valorization of food waste to create value-added products (Sharma et al., 2021). By converting food waste into useful materials or products, such as bio-fertilizers, animal feed, or functional food ingredients, the circular economy supports the development of a sustainable food system that emphasizes resource conservation and environmental stewardship (Sharma et al., 2021). This system is characterized by: waste reduction and resource optimization, nutrient retention and reuse; sustainable production cycles; and customization for functional nutrition.

Innovative solutions: The role of 3D printing

Traditional food processing and waste management techniques, such as composting, anaerobic digestion, and conventional upcycling methods, have long been utilized to manage food waste. While these methods contribute to waste reduction and energy recovery, they have notable limitations in terms of efficiency, scalability, and value addition. Composting, for example, requires long processing times and significant space, while anaerobic digestion primarily produces biogas but lacks direct applications for food-grade product recovery (Esparza et al., 2020). Conventional upcycling methods, such as extrusion and dehydration, often degrade the nutritional and sensory properties of food waste, limiting their commercial viability (Trabold & Nair, 2018).

Among the emerging technologies that resonate with the principles of the circular economy, is 3D printing. Also known as additive manufacturing, 3D printing has emerged as a technology whose development embodies layer-by-layer depositing of material as a customized and complicated structure (Padhiary, Barbhuiya, et al., 2024). In the food industry, it moved beyond novelty to a sustainable tool for valorizing waste. Utilizing food waste and by-products as raw materials for printable formulations, 3D printing offers an innovative solution to transform these undervalued resources into nutritious, visually appealing, and functional food products (Tyupova & Harasym, 2024; Yoha & Moses, 2023). Personalization of food design and composition are among the advantages of 3D food printing, catering to individual dietary preferences and nutritional needs (Pradhan et al., 2024; Varghese et al., 2020). For example, fruit and vegetable by-products can be used to formulate nutrient-dense powders that can be added to printable formulations to increase the nutritional value of the final product (Tomašević et al., 2021). Furthermore, 3D printing allows for the production of complex shapes and textures, thereby making food more appealing to the consumer while also minimizing waste. Traditional methods discard up to 40 % of food waste, whereas 3D printing can utilize over 90 % of input materials, minimizing waste. Conventional thermal processing can lead to 30–50 % loss of essential nutrients, whereas 3D printing, particularly when combined with non-thermal methods, retains up to 85–95 % of nutrients (Esparza et al., 2020; Trabold & Nair, 2018). Unlike extrusion or dehydration, 3D printing allows for precise control over texture, shape, and ingredient composition, making it suitable for functional and personalized nutrition. Traditional processing methods consume higher energy due to prolonged drying, milling, and reformulation steps, while 3D printing operates with 20–30 % lower energy consumption by optimizing material deposition and reducing processing time (Trabold & Nair, 2018).

Linking sustainability and innovation

The inclusion of 3D printing in food waste management aligns with the general objectives of sustainability: to reduce the environmental impacts. Landfilling and incineration are traditional waste disposal methods that emit greenhouse gases, such as methane, and cause pollution. Food waste conversion into printable materials not only saves disposal costs but also generates a new source of revenue for the food industry. It can bring a reduction of around 40–60 % in waste disposal (Pant et al., 2023; Yoha & Moses, 2023). This step progresses the economic value of waste valorization by supporting sustainable practices throughout the supply chain. Above and beyond reducing waste, 3D printing also fosters potential innovations in innovation, as interdisciplinary teamwork in food science, material engineering, and technology will promote methods in the food industry's production processes

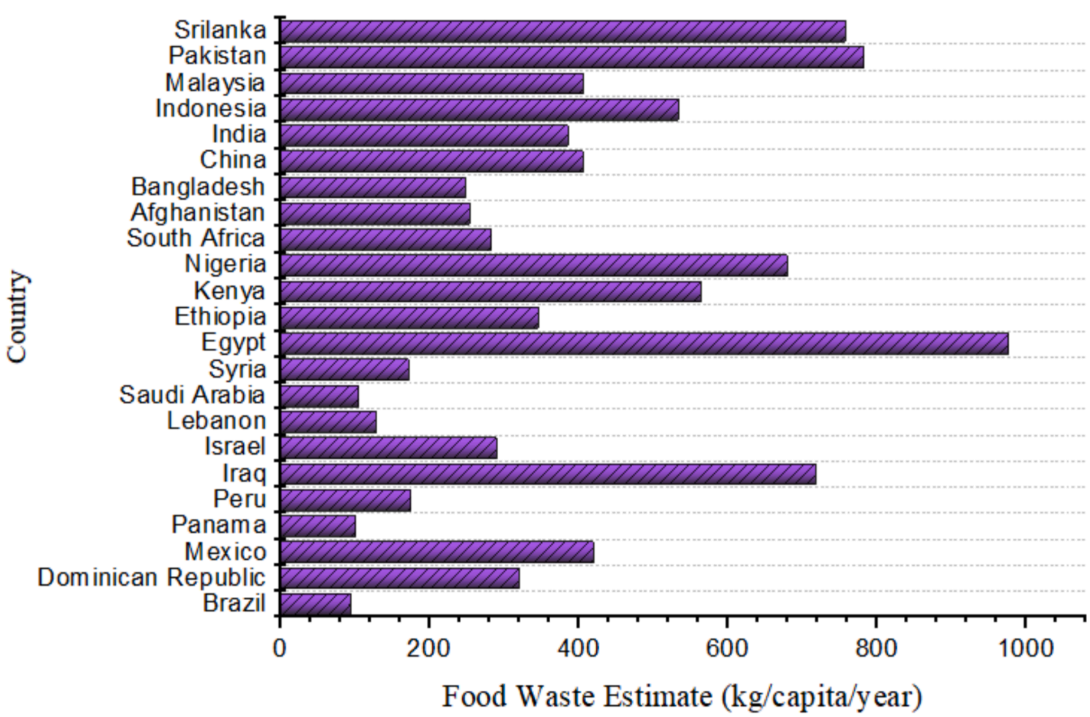


Fig. 1. Global food waste statistics with bar charts representing major countries contributing to global food waste in different regions: Latin America and the Caribbean region, West Asian region, African region, and Asia Pacific region (*Data adapted from UNEP 2023;*).
Source: https://wedocs.unep.org/handle/20.500.11822/45230

(Padhiary, Barbhuiya, et al., 2024).

Literature review methodology

PRISMA protocol

A comprehensive and transparent review of the literature on the utilization of 3D printing technology in food waste valorization was conducted using the systematic reviews and *meta*-analysis (PRISMA) protocol following the literature of Doustmohammadian et al. (2022). This systematic methodology identified prominent subjects and patterns in the literature, providing useful observations into contemporary research on the sustainability of 3D printed printing, as well as their application in upcycling food processing by-products. The study seeks to reduce bias and guarantee the dependability and accuracy of the results by adhering to the PRISMA criteria. The Scopus database is chosen for its extensive coverage of peer-reviewed research articles and citations across a wide range of international journals. An examination of the utilization of 3D printing in various applications reveals a consistent rise in the number of published works from 2015 to 2024 (Fig. 2a). Notably, there has been significant research conducted on the subject of Agricultural processing, followed by engineering and chemistry (Fig. 2b). The majority of research in this domain is conducted in China (around 23 %); followed by India (21 %) and US (13 %) (Fig. 2c). Fortunately, these researches are being funded and sponsored by a number of Government agencies and organizations like National Natural Science Foundation of China, European Commissions, Government of Jiangsu Province, Ministry of Food Processing Industries of India and so on (Fig. 2d).

Bibliometric analysis for interlinkage of keywords using VOS viewer

A bibliometric analysis is undertaken using VosViewer to examine the trends and interconnections of keywords in the literature survey. This analysis aims to visually depict the interconnections among fundamental concepts and issues in the domain of 3D Printing as they relate to food waste upcycling. A bibliometric analysis was performed in VosViewer software following the methodology of Padhiary, Saha, et al. (2024). A keyword network diagram (Fig. 3) was constructed based on 81 most occurring keywords out of 1864 from a total of 569 publications from the Scopus database with the search keywords 'Food Waste'; 'Food Processing By-products'; '3D Printing'; 'Valorization' and 'Printing Parameters'. The diagram showed 8 clusters, along with lines of different colors and thicknesses connecting these terms, showing the strength or frequency of their connections. The central term "3D Printing" is highlighted in large font, indicating its importance. In the network, the keywords '3D Food Printing' seemed to be occupying the second largest nodes and are well inter-connected with other major nodes of different clusters like "Rheology" and "Mechanical properties" indicating the significant correlation of 3D food printing with the rheological and mechanical properties of the material; which is quite similar to the findings of bibliometric analysis by Tyupova and Harasym (2024).

There is another separate red-colored cluster with the central word "Food Waste"; has been found to be moderately connected implying that 3D Printing is a state-of-the-art technology and is a prime thrust area for research exploration in food waste management. The "Rheology" cluster is related to terms such as "textural properties", "hydrocolloids", "post-printing" and "printability". This implies the importance of material rheology in determining extrudability, texture profile, and additives requirement for the final product after printing. Similarly, the "Food waste" cluster is associated with concepts like "Sustainability", "circular bioeconomy" and "valorization". Likewise, the green-colored cluster of "mechanical properties" is associated with concepts like "Process parameters" and "optimization" which are very crucial for printing operations. In contrast, the keyword 'Soft robotics' was found to be very poorly connected with all other keywords, implying scanty research on the intervention of emerging technologies like machine learning (ML) and artificial intelligence (AI) in 3D printing operations. This knowledge

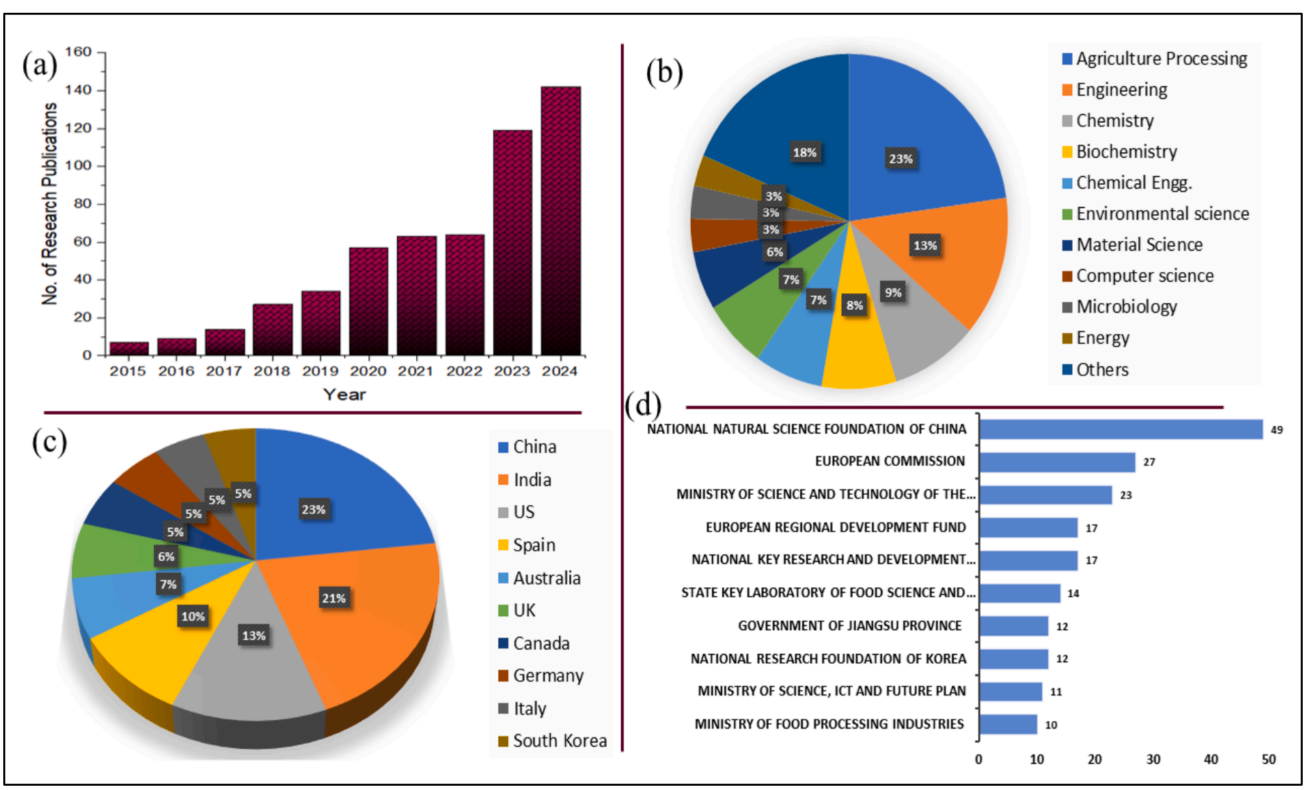


Fig. 2. Scholarly works worldwide on 3D Food Printing for waste valorization in Scopus database(a) Number of research publications from 2015 to 2024; (b) Fields or domains of studies; (c) Countries active in studies; (d) Funding sponsored by major Departments/ Agencies (Data taken from Scopus Database on 10th Dec 2024).

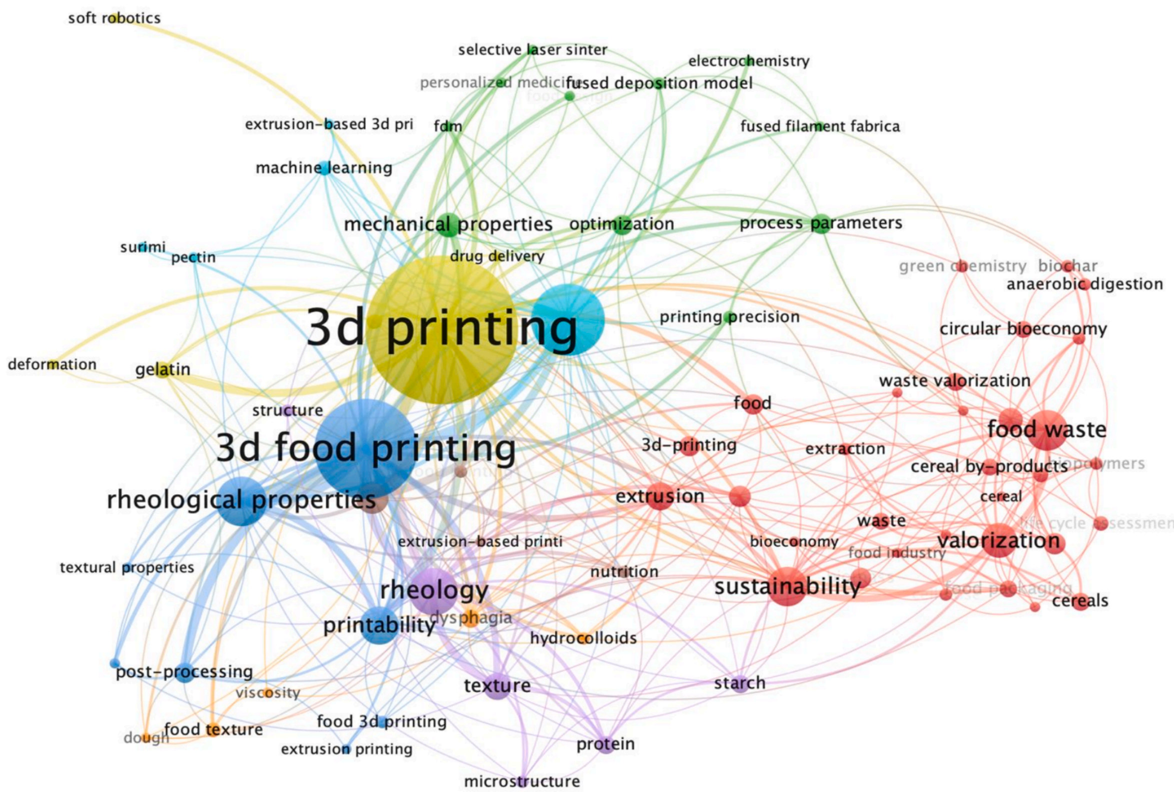


Fig. 3. Keyword interlinkage network based on 81 most occurring keywords out of 1864, with the number of occurrences of a keyword being $\geq$ 4 (Based on 569 publications accessed from Scopus database with keywords 'Food Waste, Food Processing By-products, 3D Printing, Valorization and Printing Parameters' (10th Dec 2024).

will be pivotal in directing future study endeavors and thereby mitigating carbon footprints to establish circular bio-economy concepts. Several researchers like (Iftekar et al., 2023; Nazir et al., 2023; Padhiary, Barbhuiya, et al., 2024; Pradhan et al., 2024) suggested that the key challenges faced include ensuring robustness against variable conditions, the high initial investment for scaling up, post-printing deformations, and other technical defects. Overcoming these regulatory and operational hurdles with process optimization, technological upgradation, and food printers particularly dedicated to food waste printing; are essential for effective real-world implementation in industries. However, to keep the discussion focused and updated, an attempt was made to include only the most impactful research articles as per the PRISMA flowchart shown in Fig. 4**.**

Food processing wastes and by-products

Sources and composition of food wastes

These food processing wastes and by-products, in this global food supply chain, are something that can hardly be avoided. Such materials, often discarded, possess much potential for valorization using emergent technologies, such as 3D printing. Surprisingly, most food processing by-products retain their nutritional profile and hence are richer than the main product (Nath et al., 2023). Citrus peels from oranges and lemons have been claimed to have many amounts of pectin, antioxidants, vitamin C, essential oils, and fibre. In the case of oranges, they can contain five times more vitamin C than what the fruit holds in itself (Guo et al., 2024). Fruits and vegetables are amongst the most processed categories of foods. They all, in this context, provide ample waste as peels, seeds, cores, pulp, and pomace (Guo et al., 2024; Šeregelj et al., 2021). Apple pomace is a by-product of juice extraction and has a rich content of polyphenols and dietary fibre; thus, this residue could represent a functional and nutritional additive (Kauser et al., 2024). Carrot and beet pulp, being widespread juice-extraction by-products, are rich in beta-carotene and other antioxidants, making possible the production of attractive and nutritionally dense printed products (Tiwari et al., 2019; Tumbas Šaponjac et al., 2016). All these materials are widely available and geographically diffused, and they ensure continuous raw material availability for valorization. The seafood industry also generates millions of tons of waste every year, which includes shells, bones, scales, and cartilage; thus, their large-scale use is required (Coppola et al., 2021; Naseem et al., 2024). Seafood wastes, such as shrimp shells and crab exoskeletons, are mainly composed of chitin, which can be converted into chitosan for creating biocompatible or extrudable materials (Naseem et al., 2024). Fish bones and scales are rich in collagen, calcium, and phosphorus; these materials can be repurposed for fortification in functional foods or in edible scaffolds (Xia et al., 2024). Thus, utilizing seafood waste aligns with coastal economies' sustainability initiatives, reducing the ecological burden of disposal.

Majorly, the industrial food waste from cereal, legume, and pulse processing includes bran, husks, hulls, and starchy residues. The rice husks and wheat bran are rich in insoluble fibre, which would improve the mechanical properties of the packaging material. Additionally, rice bran is a beneficial source of essential fatty acids and B vitamins that add functional benefits (Srivastava et al., 2023). Even protein-rich residue like soybean meal is ideal for specific dietary needs and caters to personalized nutrition for certain consumer categories. Other industries, like dairy and meat industries, generate by-products such as whey, skim milk, and animal bones. Whey, being a protein-rich liquid by-product from cheese-making, can serve as a functional ingredient in creating protein-enhanced foods, beverages, and health drinks (Mehmood et al., 2019). Animal bones and connective tissue are significant sources of gelatin and collagen, which add texture, viscosity, and rheological

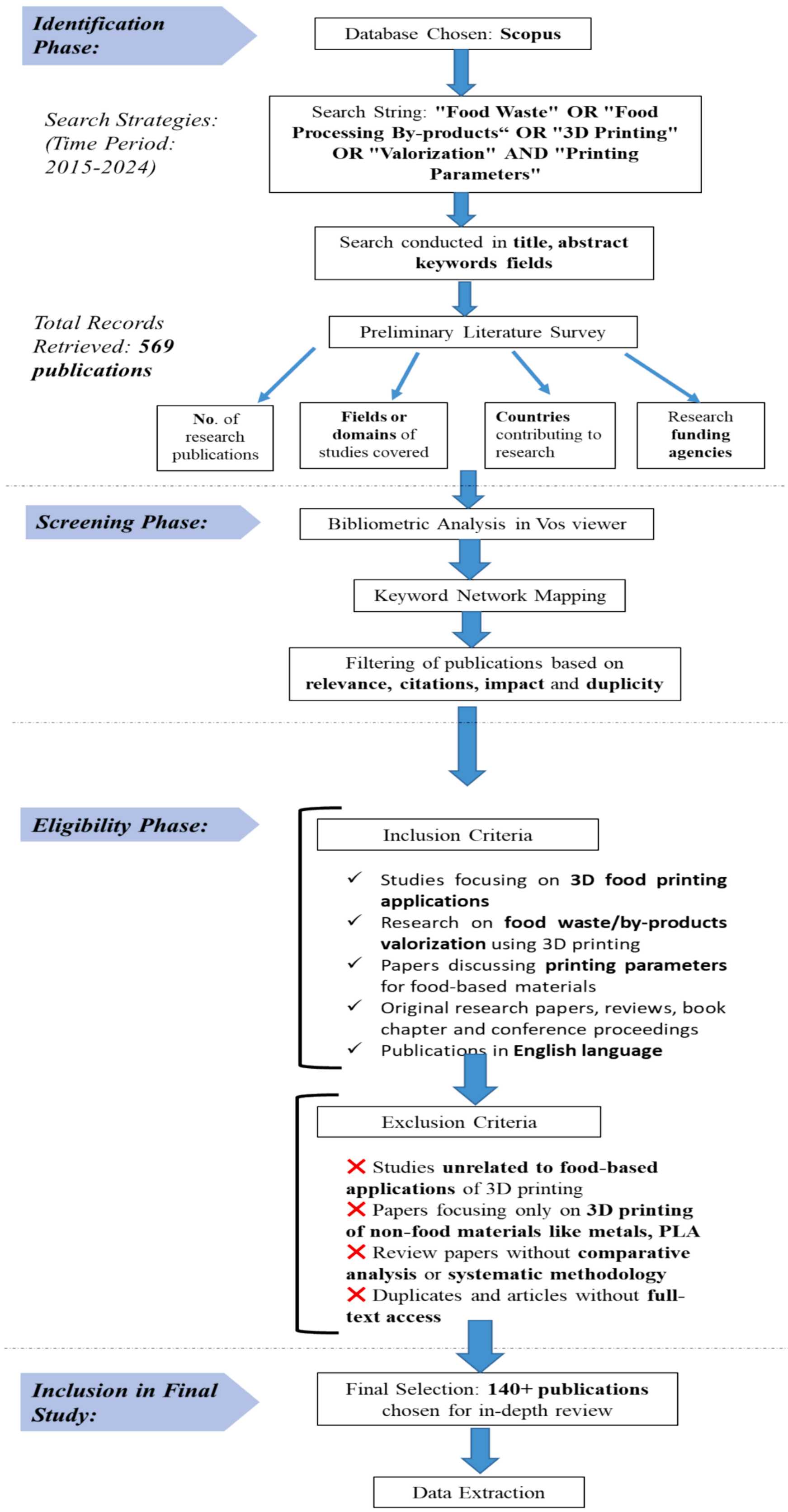


Fig. 4. Flowchart of the PRISMA methodology used in the study for the literature search.

stability. Such by-products are versatile and widely used in high-value food and non-food applications (Xia et al., 2024). The uniformity and global availability of these by-products make them attractive for scalable valorization efforts. Fig. 5 categorizes various types of food waste, including agricultural waste, processed products, retail product losses, and household waste, and outlines the sources that contribute to this global food waste.

Physicochemical and functional properties of food wastes

The physicochemical and functional properties of the waste streams would thus significantly affect their reusability and valorization. In addition, it determines the processing that is mainly needed for their valorization as well as economic feasibility to a great extent. Examples of such highly moist materials include vegetable pulp, requiring stabilization or drying before processing since it may quickly undergo microbial action leading to spoilage (Yan et al., 2023). The gelation and rheological stability of food are contributed to by materials such as pectin, from citrus peels, and collagen, from bones (Gao et al., 2024; Guo et al., 2024). Uniformity of particle size of processed by-products ensures smooth extrusion and consistency. Other functional properties of by-products, like emulsifying, gelling, or thickening, are very important in innovative formulations and valorization as illustrated in Table 1. Chitosan originating from seafood waste is known for its anti-microbial properties, therefore it is very suitable for extended shelf-life applications in food products (Gao et al., 2024). Wheat bran enhances texture and structure, creating strong yet edible products, making them suitable for many challenging bakery applications (Bilal et al., 2024).

Environmental and economic impacts of food waste disposal

The valorization and reutilization of food waste streams are critical, catering to their possible environmental and economic repercussions. Improper disposal of food processing waste results in significant environmental issues like greenhouse gas emissions, and loss and contamination of soil, water, and other vital natural resources. Organic waste in landfills generates methane, a greenhouse gas over 25 times more potent than carbon dioxide (Girotto et al., 2015). Thus, global fruit and vegetable waste contributes millions of metric tons of methane annually. Liquid effluents from food processing can leach into soil and water systems, causing eutrophication and biodiversity loss. Valuable nutrients and bioactive compounds are often wasted, contributing to resource inefficiency in the food supply chain (Girotto et al., 2015).

Fig. 5. Types and sources of food wastes.

For the food processor, waste disposal presents a financial liability. The various forms of landfill charges, transportation fees, and other regulatory compliance put an extra price tag on operational costs. Also, the missed chance to obtain further value from the by-products amounts to potential losses in revenues (Tonini et al., 2018). Thus, lies the imperative necessity to comprehend value-added potential in waste valorization. In many ways, the economic benefits of converting waste into value-added products far outweigh the costs of disposal. Using waste materials in processing reduces raw material expenses while cutting disposal costs. Innovations such as nutrient-dense, waste-derived 3D-printed foods open new markets for personalized nutrition and sustainable products (Tyupova & Harasym, 2024). Valorizing food waste supports the transition to sustainable production systems, thereby aligning with global sustainability goals like the UN's Sustainable Development Goals (SDGs) which include circular economy objectives (Tyupova & Harasym, 2024). Table 1 provides a summary of the major nutritional, physicochemical, and functional properties of food waste components that are suitable for 3D printing, based on their composition, structural benefits, and potential for product development.

3D food printing assay

Pre-requisites and printing procedures

In 3D food printing, edible pastes, gels, or powders are utilized as printing materials, allowing customization of the final product to satisfy consumer preferences and dietary requirements. The key benefit of 3D printing lies in its potential to alter nutritional, flavor, and texture profiles to meet individual needs (Pradhan et al., 2024). Before starting 3D printing operations, a computer-aided (CAD) design of the model has to be created in software like SolidWorks, Autodesk Fusion 360, etc.; after that, slicing of the corresponding Stereolithographic (STL) file in some slicing software such as Prusa Slicer, Ultimaker Cura, etc, as done by Saha et al. (2023). Some of the major prerequisites before printing involve setting printing parameters and calibrating the printer with respect to the printing bed coordinates. The mechanism of 3D food printing technology is the robotic building process that includes inputting food elements and their extrusion along a predetermined way, which leads to the deposition of successive layers. The fused deposition technique is utilized in extrusion-based 3D food printing, in which a syringe-based extruder injects a highly viscous food slurry (Raja et al., 2023).

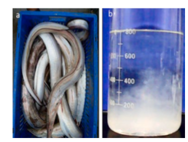
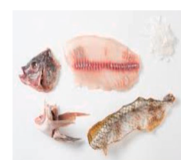
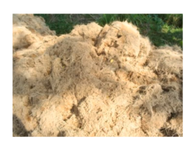
Fig. 6 shows the typical flowchart of different steps and procedures involved in 3D food printing assay. It also depicts different types of extrusion 3D printing including soft-element extrusion, melted-element extrusion, and gel-forming extrusion. In soft-element extrusion, additive manufacturing creates three-dimensional structures by depositing and fusing self-supporting layers of materials like meat paste, dough, mashed potatoes, taro paste, fruit and vegetable mixtures, and processed cheese. The material's viscosity is critical, allowing extrusion through a fine nozzle while ensuring the structure maintains integrity after deposition. For melted-element extrusion, suitable candidates are chocolate, pastes, powders (or solid pieces), and, less commonly, filaments in food applications (Jiang et al., 2020). The necessary temperature control has to be done to make sure that it prints well. For gel-forming extrusion, the process will depend on the rheological properties of polymers and the gelling process itself. The solution of the polymer should exhibit viscoelasticity before becoming a self-supporting gel (Wang et al., 2023). This alteration should be performed before layering so that the printed structure would be stable. This technique can be applied in printing starch, pectin, pea, and soybean proteins, K-carrageenan, xanthan gum, sodium alginate, etc (Narayanan et al., 2016; Wang et al., 2023).

Table 1
Nutritional, physicochemical and functional properties of some major food waste components.

Food wastes (type/ sources)	Nutritional factors	Physicochemical properties	Functional Properties	Suitability for applications	Images	Ref.
Orange peel waste	High in pectin, cellulose, and hemicellulose; flavonoids like hesperidin, naringin, and polymethoxyflavones; contains beta-carotene, d-limonene, ferulic acid caffeic acid	XRD exhibits amorphous and semi-crystalline patterns; high anti-oxidant activities, TPC (63.20—–169.56 mg/g) and TFC (0.13.89—–29.75 μg/g); moisture content (70–80 %)	Adequate water and oil absorption capacities of 1 g/g and 3—5 g/g at 25 °C respectively; excellent gelling properties	Ideal fiber supplement in bakery products; can be used as natural preservatives; gelling and flavoring agent		(Guo et al., 2024)
Carrot waste extract, pulps and pomace	High carotenoid (192.81 ± 0.32 mg carotenoids/100 g DW), and bioactive content (total phenolic: 78.12 ± 0.35 g GAE/100 g DW), and antioxidants by DPPH (823.14 ± 0.54 mM TE/100 g DW)	pH ranges from 5.5 to 6.5 (slightly acidic); contain 5–15 % TSS, comprising sugars, acids, and other soluble compounds; pomace extracts viscosity varies between 1.5 to 3.5 mPa·s; moisture content (7–9 % db)	Extracts contain soluble fibers, proteins, and saponins, which can act as natural emulsifiers and stabilizers, contain prebiotic fibers, including pectin, cellulose, and hemicellulose.	Colorants in nutritional food formulations		(Šeregelj et al., 2021; Tiwari et al., 2019)
Tomato waste	Contains rich dietary antioxidants including carotenoids, especially α-carotene, β-carotene, lycopene and lutein. Also contains fibre pectin,	Poor water retention (0.2 g/g), low bulk density (0.47 g/cc); moisture content (90–95 %)	High oil absorption capacity (2.6–3.4 g/g) that is beneficial in food coatings or flavour delivery	Valuable ingredient for food and nutraceutical applications and can also extend shelf life		(Catalkaya & Kahveci, 2019; Chabi et al., 2024; Namir et al., 2015)
Banana peel waste	Contains pectin, high dietary fibre (20–30 %), cellulose and hemicellulose	High moisture content (70–80 %),has a characteristic yellow–brown colour, slightly crunchy texture	Good absorbent properties; OAC (35–115 g/g), thickening and gelling properties	Thickening and stabilizing agents in food applications		(Rivadeneira et al., 2020)
Beetroot Pomace	Rich in bioactive compounds and pigments; high levels of betalains, viz; betacyanins and betaxanthins,	pomace is rich in mineral content (K, Mg, Fe), exhibits viscoelastic behaviours; Betalains degrade at higher temp., moisture (6.82 ± 0.03 %)	Enhance the the oxidative stability of food products; adequate WHC (5.040 ± 0.104 g/g) and OAC (2.206 ± 0.064 g/g)	Pharmaceutical applications and encapsulation for pigments/colorants in food applications		(Sahni & Shere, 2017; Tumbas Šaponjac et al., 2016)
Grape pomace	contains flavonoids, tannins, anthocyanins, and phenolic acids, linoleic acid (an omega-6 fatty acid), vitamin E, and phytosterols.	Polyphenol degradation starts under high heat, light, or pH extremes; strong radical-scavenging activity; moderate thermal stability; moderate water content (55–75 %)	Grape seed oil contributes to improved lipid profiles and oxidative stability in emulsions and dressings.	Formulation of functional muffins; bakery products etc.		(Troilo et al., 2022; Yu & Ahmedna, 2013)
Broccoli stalk	Rich in Pectin, glucosinolates, phenolics, and flavonoids, contains both soluble and insoluble fibre, vitamin C, vitamin K, K, Ca, Mg,	Glucosinolates degrade into sulforaphan under enzymatic and thermal stress, good water-holding and gel-forming properties; very high moisture content of 91.24 %	Natural thickening agent; protects oxidative stress	Thickening and stabilizing agents in food applications		(Núñez-Gómez et al., 2022; Petkowicz & Williams, 2020; Yan et al., 2023)
Blackberry wastes	High dietary fibre and antioxidant; anthocyanins, flavonoids, ellagitannins, and phenolic acids; contains residual natural sugars	Anthocyanins degrade at high temperatures, light, or pH variations; porous, fibrous structures, contributing to high water-holding capacity	Anthocyanins contribute to vibrant color and mild berry-like flavour; can improve mouthfeel and texture	Application in health beverages, confectionery, and baked foods		(Jiang et al., 2022; Sozzi et al., 2021)
Maize waste	High in insoluble fiber, including cellulose, hemicellulose, and lignin; bran contains resistant starch	Potential bioactivity and antioxidant properties; XRD shows semi-crystalline structure	Texture enhancer; offers a mild, nutty flavour; improves viscosity and stability in emulsions and pastes.	Food, packaging and pharmaceutical applications		(Pashazadeh et al., 2021; Vitez et al., 2020)

(continued on next page)

Table 1 (*continued*)

Food wastes (type/ sources)	Nutritional factors	Physicochemical properties	Functional Properties	Suitability for applications	Images	Ref.
Soybean residues	Retains bioactive compounds like genistein and daidzein, known for their antioxidant and phytoestrogenic properties. high in insoluble fibre	XRD suggest an amorphous structure for most polysaccharides with limited crystallinity from cellulose; fibrous nature contributes to a chewy texture and increases viscosity in formulations.	Can improve the viscosity (100 mPa.s) and gelation of soups, sauces, and emulsions; offers a mild bean flavour, high moisture of 70 %	Protein and fibre-rich functional food		(Chen et al., 2014; Li et al., 2020; Lu et al., 2022)
Pineapple peels, crown leaves	Extracted for Vanillic acid and vanillin (aromatic compounds); contains phenolics, flavonoids, beta-carotene (provitamin A) and bromelain, known for antioxidant, anti-inflammatory, and digestive properties.	XRD reflects reflects semi-crystalline regions; Bromelain exhibits proteolytic activity.	High moisture content (82.35 %) and oil-binding capacity improve texture and reduce syneresis.	Flavoring agents in food applications		(Tang & Hassan, 2020)
Marine eel fish skin	Rich in type I collagen, a crucial extracellular matrix (ECM) protein;	Excellent water retention with a porous microstructure; resistant to enzymatic degradation; viscosity of 3.2–7.12 cP	Flexible and elastic, mimicking the mechanical properties of soft tissues; non-toxic and immunologically inert	Collagen for tissue engineering applications and bio-composite scaffolds and filaments.		(Govindharaj et al., 2019; Veeraraj et al., 2013)
Fish wastes and by-products	Contains fish protein and its derivatives with bioactive peptides; rich sources of Ca, P and Mg, EPA and DHA, Omega-3-fatty acids	SEM reveals fine microstructures in powdered forms, enhancing solubility and dispersion; crystalline structure observed in XRD; improved water retention	Collagen and gelatin improve texture, elasticity, and mouthfeel; offers umami flavour enhancement and functional aroma;	Functional ingredient for food fortification		(Coppola et al., 2021; Naseem et al., 2024; Olaniran et al., 2024; Xia et al., 2024)
Shrimp shell waste	Highly chitinous; contains residual proteins and amino acids; contains astaxanthin (carotenoids)	Suitable for moderate thermal processing; XRD shows crystalline structure of chitin, contributing to mechanical stability	chitin can be converted to chitosan, a bioactive polymer with antimicrobial, antioxidant, and emulsifying properties.	Thickening, stabilizing, and antibacterial agents		(Benhabiles et al., 2013; Gao et al., 2024; Xia et al., 2024)
Sago pith waste	Rich in resistant starch, low protein and hypoallergenic.	SEM reveals smooth, round, and elliptical granules; high gelatinization temperature; XRD represents an A-type crystalline structure, 90 % wb moisture content	High water absorption and swelling power; high paste clarity, low viscosity breakdown, and good freeze–thaw stability.	Thickening, gelling, stabilizing agents in gluten-free formulations); also used in making bio-plastic films		(Luthfi, 2024; Santoso, 2018)
Artichoke waste	Exclusively rich in dietary fibre (soluble and insoluble); contains chlorogenic acid, cynarin, flavonoids, Inulin	Moderate thermal stability; semi-crystalline structures in fibres and inulin, calorific value (19.1 MJ/kg)	Excellent water-binding properties (6.61 g/g) and solubility; also good oil holding capacity	Dietary fiber-rich health foods or therapeutics against Cd poisoning		(Zhu et al., 2022)
Rice husk	High in insoluble fiber, including cellulose, hemicellulose, and lignin, also in silica and trace minerals; Contains antioxidants such as ferulic acid, p-coumaric acid, and flavonoids	Shows semi-crystalline structures due to cellulose and silica content; phenolic compounds act as natural antioxidants, extending shelf life, moisture content (10–16 %)	Higher water holding ability (251 %) and oil retention; adds a mild, nutty flavor when finely processed; improves cohesion in food products	Adds flexibility to baked products		(Bajsic et al., 2021; Srivastava et al., 2023)
Corn husk	Contains ferulic acid, p-coumaric acid, and flavonoids, lignin, cellulose and hemicellulose	Semi-crystalline structures due to cellulose content, which influences its functional and mechanical properties; enhances viscosity (31.6 Pa) and flow properties	Excellent water-binding ability (200 %); cross-links with polysaccharides to form natural gels; provides mild, earthy flavours	Can be used for antimicrobial biodegradable packaging film		(Chawla et al., 2023; Ratna et al., 2022)

(*continued on next page*)

Table 1 (*continued*)

Food wastes (type/ sources)	Nutritional factors	Physicochemical properties	Functional Properties	Suitability for applications	Images	Ref.
Wheat bran	High in both insoluble (cellulose, hemicellulose, lignin) and soluble (arabinoxylans, beta-glucans) fibers; rich in ferulic acid, vanillic acid, and flavonoids	Displays amorphous and semi-crystalline structures; SEM images shows fibrous and rough surface, viscosity (3.6 dL/ g), moisture (2.17–8.5 %)	High water and oil absorption (141.56 %); increases dough viscosity and elasticity; enhances cohesion; adds a nutty flavour and coarse texture	Suitable for baking, extrusion, and mild thermal processing based food application		(Bilal et al., 2024; Onipe et al., 2015)
Fruit and vegetable waste	Natural cellulose-rich structure; rich in flavonoids, natural oils, phenols etc.	XRD reveals a combination of amorphous and crystalline structures; excellent flow properties and easy to mould;	High mechanical strength and durability; naturally colourful and eco-friendly; good elasticity and flexibility.	Suitable for making Pulp based vegan leather		(da Silva Simão et al., 2020; Patil et al., 2024; Sarma et al., 2023; Tauhiduzzaman et al., 2024)

*XRD: X-ray diffraction; SEM: Scanning electron microscopy.

Printing parameters

Printability of a material is a rather complex term that depends on many material properties and also on critical printing parameters. Temperature is one of the most critical factors in 3D food printing because it influences material behaviour, structural integrity, and food safety (Kadival et al., 2023). For extrusion-based printing, chocolate must be tempered exactly to keep the consistency of the material during printing. In such materials as dough, where printing is a high-temperature process, this becomes crucial but brings difficulties for sensitive nutrients with respect to heat (Pradhan et al., 2024). The nozzle diameter is the other printing parameter that affects mostly resolution and printing speed, thus print quality and accuracy. Smaller nozzles make more detail-rich printed products but take longer in the printing process and require close regulation of the viscosity of materials used. On the other hand, chunkier structures, such as thick dough layers or purees, can be accommodated with bigger nozzles (Pradhan et al., 2024). Thus nozzle diameter optimization is critical for efficiency improvement of the process.

Printing speed and layer height must also be optimized to ensure that the final product is structurally stable because high-speed printing often sacrifices precision and is linked to risks of layer collapse in softer materials (Pradhan et al., 2024). Thus, for upscaling 3D food printing at the industrial level and increasing overall throughput, it is necessary to introduce a large number of 3D printers running in series or tandem with multiple extruder assemblies, rather than increasing the speed of the individual printer. Layer height dictates texture and mouthfeel; lower heights give smoother surfaces, whereas higher ones yield rougher textures. Pradhan et al. (2024) optimized printing parameters for composite gluten-free dough and reported an increase in printing efficiency by up to 30 %. Similarly, properties of food materials, such as viscosity and flow properties (shear thinning and shear thickening), are also important parameters in determining the printability of a food material (Kadival et al., 2023). In fact, viscosity is one of the main parameters that determine extrudability for 3D printing. For instance, purees of vegetables have high shape retention but can block printer nozzles. Low-viscosity materials are quite fluid but can lead to the problem of spreading and loss of accuracy in the layer. Hence, some stabilizers, such as pectin or gelatine, are added to provide ideal flow properties (Kadival et al., 2023). Many times, certain additives and hydrocolloids, including xanthan gum, guar gum, sodium alginate, etc., are used to support the printing process and reduce deformation post-printing.

Post-printing operations

Improvements in post-processing of the 3D-printed products, especially those that are cold-extruded, could relate to improvements in structural stability, shelf life, palatability, and/or digestibility (Pradhan et al., 2024). Inappropriate types and conditions of post-processing, however, can negatively affect the quality of 3D-printed structures. Irrespective of which post-processing process is selected for the stabilization process, because quality and acceptability of the product are determined post-processing, the best post-processing method along with the corresponding best operational parameters suited for the involved products has to be optimized and maintained so as to maintain these desired visual, mechanical, sensorial, and nutritional qualities (Varghese et al., 2020). One of the most common is drying, which also stabilizes such 3D-printed foods by reducing their moisture content levels. Most often, air drying is done for 3D-printed products like crackers or breadsticks, where a crisp texture is desired (Pradhan et al., 2024). Freezing is also used for fruit-based prints to retain nutrients and improve the shelf life of delicate structures. Cooking and baking ensure the ready-to-eat palatability and food safety of the final product. Dough-based products are subjected to baking, which sets up their structure and enhances flavor and texture (Pradhan et al., 2024).

For protein-based prints, sous-vide or steaming seems to be the best because it ensures uniform cooking without sacrificing delicate structures. Sometimes setting and stabilization operations are also needed post-printing, like gelatin or chocolate, to keep them in their shape and consistency (Berglund et al., 2020). Sometimes, food-grade printers are modified and fabricated with a specialized cooling chamber and attachments that can quickly solidify chocolate-based prints for intricate designs (Lanaro et al., 2017). Dairy-based or protein-enriched products can stabilize and preserve final output through the use of refrigeration. Post-printing, we sometimes apply surface treatments like glazing or coating to enhance appearance, texture, or shelf life. For example, a sugar glaze can provide a glossy finish, while a thin layer of chocolate can enhance the flavor and structural stability of the final printed product (Liu et al., 2020). The success of 3D food printing depends on the accuracy of the integration of printing procedures, parameter optimization, and post-processing steps. Industry-level management of printing parameters and post-printing operations will guarantee the precision, stability, and scalability required for a widespread adaptation of this new technology.

Advantages of 3D printing over conventional methods

A revolutionary method of food processing is provided by 3D food printing, particularly when it comes to repurposing food waste into useful goods. 3D printing offers accuracy, personalization, and material efficiency in contrast to conventional food processing techniques, which depend on mass manufacturing and uniform shaping. The main benefits

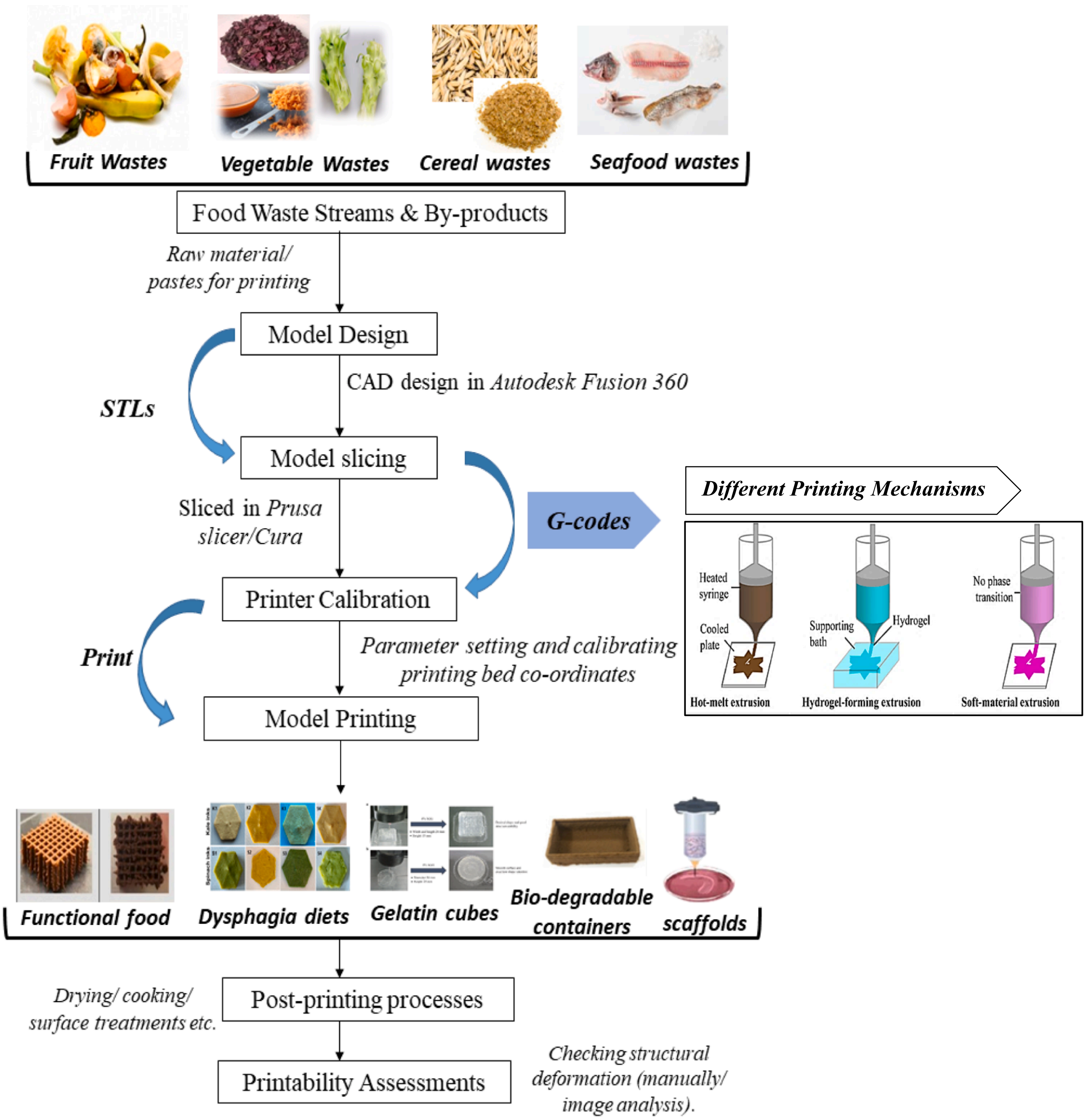


Fig. 6. Extrusion-based 3D printing workflow for food waste valorization.

of 3D printing over traditional food preparation methods are listed below.

High precision and customization

3D printing offers a more complex and customizable alternative to traditional food processing methods, allowing for the creation of novel textures and food structures. This technology can be used for personalized nutrition applications, allowing for precise ingredient control for different consumers. It achieves near about 100 % shape flexibility, enabling customized portion sizes and designs, and reduces product rejection rates due to non-conformance in traditional processing (Pradhan et al., 2024). 3D printing offers a solution to traditional food processing issues by allowing precise control over layer thickness and density, improving mouthfeel, crunchiness, and aeration (Varghese et al., 2020). This technology can create meat-like textures using plant-based proteins, enhancing consumer acceptance of alternative protein products and enabling multi-textured food designs not possible with traditional methods.

Enhanced nutrient retention

Traditional food processing methods like frying, boiling, and baking can lead to nutrient degradation due to high temperatures, prolonged cooking, and exposure to oxygen. 3D printing, when combined with low-temperature drying or controlled post-processing, helps retain vital nutrients, such as vitamin C and antioxidants in fruit-based snacks (Varghese et al., 2020). Controlled-temperature drying retains up to 85 % of vitamin C, and fruit peel-derived 3D-printed products have 25 % higher polyphenol content compared to traditional extrusion methods (Pradhan et al., 2024; Saha et al., 2024).

Resource utilization and sustainability

Traditional food processing often discards valuable by-products due to difficulties in reshaping or incorporating them into new products. 3D printing allows for precise material deposition, allowing high-fibre, high-protein waste fractions to be incorporated directly into printable formulations. For example, shellfish waste can be micro-milled and blended into 3D printing inks, enhancing calcium content by 30 % compared to conventional seafood processing by-products (Xia et al., 2024). This maximizes the use of nutritionally dense food waste and increases the economic value of waste streams. Traditional food processing generates significant by-product waste, necessitating additional refining and disposal. 3D printing, an additive manufacturing process, controls material use, reducing waste by 20–30 %. This reduces raw material consumption and energy costs by requiring fewer post-processing steps, compared to traditional extrusion methods that require 10 % material loss (Kadival et al., 2023).

On-demand, decentralized production

3D printing offers a solution to traditional food production, reducing dependence on large, centralized factories. This technology allows localized, on-demand food production, reducing transportation and storage costs. It's particularly useful in remote areas, space missions, military applications, and hospitals for personalized nutrition (Saha et al., 2024). In fact, several cafes, like food Ink, a pioneering pop-up restaurant; have been utilizing multi-nozzle extrusion systems for preparing on-spot intricate dishes along with printed utensils, everything being sourced locally. In Barcelona, the Michelin-starred La Enoteca incorporates 3D printing technology to create complex food designs that are unachievable by hand. Similarly, Mélisse in California offers printed pastries, showcasing the fusion of technology and haute cuisine. In a word, the impact is significant, simplifying the entire supply chain mechanism, reducing food transportation emissions and storage costs, and enabling food production in resource-limited settings, that too with impressive dining experience.

Enhanced food safety and hygiene

Traditional food processing increases cross-contamination and microbial growth due to multiple touchpoints. 3D printing minimizes human contact by depositing food layers in controlled environments, reducing allergen contamination risks by up to 90 % (Nath et al., 2023). This enhances food traceability and safety standards and reduces bacterial contamination risks compared to traditional processing. Moreover, it has to be noted that pre-processing and the automated, closed-loop printing system minimize human contact, reducing contamination risks. Further, in printing applications, food wastes are refined into standardized pastes, with added hydrocolloids (e.g., xanthan gum, guar gum, sodium alginate, etc.) to maintain texture and limit microbial penetration. Additionally, antimicrobial ingredients like essential oils and probiotics can also be incorporated to extend shelf life, while post-print drying and smart packaging with antimicrobial films further prevent spoilage. These innovations make 3D food printing a highly hygienic and sustainable solution for food waste utilization.

Recycling and valorization through 3D printing enable efficient utilization of food waste by incorporating fiber, protein-, and mineral-rich by-products into functional foods. Table 2 draws some of the major comparisons between 3D printing and conventional measures of food waste management like landfills, composting, incineration, etc.

Applications in food wastes valorization

3D printing of fruit wastes incorporated food

The application of 3D printing technology in the valorization of food waste has been considered to be a step forward towards more

Table 2
Comparison between 3D printing and conventional methods of waste management.

Food waste	Potential contamination/ heavy metals/ others/ negative environmental impact	Conventional method	Efficiency	Key findings (nutrient retention)	Quantitative Comparison with 3D printing (efficiency %, nutrient retention)	Ref.
Fruit & vegetable peels	Pesticide residues, microbial spoilage	Composting, landfill	50–70 %	Moderate retention (40–55 % vitamins); nutrient loss on microbial degradation	Higher efficiency (85 %), better Vitamin C retention (90 %)	(Majerska et al., 2019; Tomašević et al., 2021)
Cereal residues	Mycotoxins, chemical residues, heavy metals like Pb, As, Hg etc.	Animal feed, incineration	60–80 %	Nutrients preserved in feed (65–80 % protein), lost in incineration	Efficient (~80 %), good retention of protein (90–98 %)	(Hassan et al., 2021; Yoha & Moses, 2023)
Dairy by-products (e.g., whey, casein residues)	High BOD (oxygen demand in water), microbial contamination	Biogas, animal feed	50–75 %	Nutrient loss in biogas, moderate retention in feed	Higher efficiency (90 %), nutrient-retention (95 %)	(Accorsi et al., 2016; Ross et al., 2019)
meat processing waste	High microbial risk, pathogen contamination, nitrogen emissions	Rendering, landfill	55–75 %	High protein loss, some fat recovery	More efficient (85 %), better protein retention (88 %)	(Motoki et al., 2022; Okoro et al., 2017)
Eggshells & egg waste	Salmonella risk, pH imbalance in soil	Fertilizer, landfill	40–60 %	Calcium preserved in fertilizer, lost in landfill	Moderate efficiency (75 %), higher calcium retention (90 %)	(Dadhich et al., 2016)
Spent tea, coffee grounds, husk	Heavy metal (Pb, As) absorption, high acidity	Composting, incineration	50–70 %	Polyphenol retention (55–70 %)	Higher efficiency (82 %), better polyphenol retention (88–95 %), less CO_2 impact	(Mandal et al., 2024)
Fish processing waste	High ammonia release, microbial risk	Fish meal, landfill	60–75 %	High protein loss in landfill, omega-3 retention (50–65 %)	Efficient (85 %), protein retention (92 %), Omega-3 retention (85–92 %); low ammonia emissions	(Maihemuti et al., 2023; Wei et al., 2024)
Brewery waste (e. g., spent grains, yeast residues)	High organic load in wastewater	Animal feed, biofuel	65–80 %	Protein and fibre preserved in feed (60–75 %), lost in biofuel	Efficient (80 %), high fibre retention (88 %)	(Barbosa-Pereira et al., 2014)
starch-rich waste (e.g., potato peels, rice husks)	Fermentation risk, mold contamination	Biogas, landfill	40–65 %	Starch breakdown in landfill, some energy recovery in biogas	Higher efficiency (85 %), better starch retention (90 %)	(Pradhan et al., 2024)
Sugar-rich waste (e.g., fruit pulp, molasses residues)	Microbial fermentation, CO_2 emissions	Bioethanol, landfill	70–85 %	Nutrient conversion to ethanol, loss in landfill	Efficient (88 %), nutrient-retention (92 %)	(Erdoğrul, 2008; Santhoshkumar et al., 2024)

sustainable and circular food systems. It allows value to be extracted from previously discarded materials, such as by transforming food waste and by-products into innovative, functional, and aesthetically appealing products using 3D food printing. Fruit processing generates a broad range of wastes, such as peels, pomace, and seeds, which are all nutrient-rich with fibre, vitamins, and antioxidants. These by-products are excellent ingredients and formulations for 3D printing (Jagadiswaran et al., 2021). Orange peels can be used successfully in cookies and snacks that have been 3D printed by Leo et al. (2022). This has a high content of pectin, meaning it improves the structural integrity while offering high dietary fibre. Apple pomace, which comes from juice production, can be used for the creation of nutrient-rich fruit bars through extrusion-based 3D printing (Jagadiswaran et al., 2021). The primary issues were the uniformity of particle size, as well as hydration levels, which are crucial for maintaining printability. High sugar content in fruit residues often leads to caramelization through thermal processing, which compromises taste and texture (Da Tan et al., 2023). Therefore, a combination of fruit waste with hydrocolloids or protein-based binders could significantly improve texture and widen printable design options for intricate geometric patterns or layered structures.

3D printing of vegetable wastes incorporated food

Vegetable wastes, such as carrot pulp, beet peel, and spinach stems, are often rich in pigments, antioxidants, and fibre, making them suitable for creating colourful and nutrient-rich printed foods. Carrot and beet residues from juice extraction have been used to print vibrant, fibre-rich snacks and meal components (Feng et al., 2021; Sahni & Shere, 2017). The pigments in these by-products not only add aesthetic appeal but also contribute health benefits like improved antioxidant activity. Although layer stacking and accuracy in printing could be affected because of the relatively high moisture level in vegetable wastes, dehydration along with particle size reduction is also often necessary for such wastes. Nowadays, in plant-based meat analogs or protein-rich formulations, the incorporation of vegetable waste appears to be one of the newest breakthroughs that come with the twofold benefits of waste generation reduction and generating a high-demand product (Shireen & Wright, 2024).

3D printing of seafood by-products incorporated food

Seafood processing generates large amounts of by-products, such as shells, bones, and scales, which are rich in valuable compounds like collagen, calcium, and chitin. These materials are being explored for their functional and structural properties in 3D-printed foods. Shrimp shells have been processed into chitosan and integrated into protein bars and snacks, providing both nutritional benefits and improved textural properties (Pradeep et al., 2022). Similarly, fish bones, rich in calcium, have been used to fortify printed crackers and biscuits (Wei et al., 2024). However, seafood by-products often require extensive pre-processing, such as demineralization and deproteinization, to isolate usable components. In such cases, ensuring the removal of any residual fishy odour is also critical for consumer acceptance (Xia et al., 2024). Developing scalable pre-processing technologies to extract high-purity chitosan and collagen can expand the application of seafood by-products in functional foods and biodegradable packaging.

3D printing of cereal-based by-products incorporated food

Cereal and legume by-products, such as rice bran, wheat bran, and soybean meal, are abundant and rich in dietary fibre, protein, and bioactive compounds (Mullaiselvan et al., 2024). These materials are well-suited for creating printed food products with enhanced nutritional profiles. Rice bran has been used to create high-fibre, gluten-free 3D-printed bread, while wheat bran has been incorporated into printed crackers to improve the dietary fibre content (Saha et al., 2024). Soybean meal has been successfully used to create protein-enriched snacks and meal components (C. P. Lee et al., 2021). Certain challenges are also encountered while printing these products; the coarse texture and high fibre content of cereal by-products can lead to nozzle clogging and uneven extrusion. This is because the high content of dietary fibre and gluten-free ingredients make the product brittle as mentioned in the literature of Sarkar et al. (2024). Pre-processing methods like fine milling and the addition of binding agents can mitigate these issues.

3D printing of food from waste fractions

Food processing often results in mixed waste fractions that include a combination of fruit, vegetable, and cereal residues. These heterogeneous materials can be challenging to process but offer immense potential when combined with stabilizing agents. Composite formulations using mixed waste fractions have been developed for printing breakfast bars, cookies, and savoury snacks (Aït-Kaddour et al., 2024). Combining cereal-based by-products with other nutrient-dense residues, such as fruit or vegetable waste, can result in multifunctional food products that cater to diverse dietary needs, including gluten-free and high-protein options. For example, blending fruit pomace with cereal bran creates nutrient-rich, structurally stable products (Jagadiswaran et al., 2021). Thus, achieving homogeneity in mixed waste fractions requires advanced pre-processing techniques like milling, drying, and sieving. Additionally, the interaction of different components during printing must be carefully managed to avoid phase separation (Troilo et al., 2022). The use of advanced AI algorithms to optimize mixed formulations for consistent printability and nutrient balance can enhance the usability of such waste streams.

Other applications

In addition to food-based products, 3D printing provides a platform for the effective use of food waste and by-products in non-food applications. The most promising application is perhaps in the field of biodegradable packaging, which is a very important area of concern nowadays due to growing concerns over plastic pollution and the need for alternatives (Nida et al., 2023). By-products such as fruit peel, vegetable pieces, and the shells of the seafood hold ample polysaccharides and other proteins. Their bio precursors could further be reused into biodegradable packaging material forms that degrade 50 % faster than regular plastics (Nida et al., 2022). Polysaccharides such as starch from potato or rice waste, cellulose from fruit pomace, and chitosan from shrimp shells are the most commonly used base materials for packaging. These biopolymers are abundant in food waste and offer the necessary mechanical strength and barrier properties for packaging. Proteins such as zein from corn and soy protein isolate from soybean waste add flexibility and durability to the packaging materials (Lu et al., 2022). Sometimes, natural additives such as glycerol are often added for better plasticity and flexibility to print in 3D. The biodegradable application of packaging through 3D printing makes it possible to do highly customized, complex designs tailored according to the needs of products.

Using extrusion-based printing is possible to produce films, pouches, and flexible wraps made from starch and cellulose-based mixtures (Nida et al., 2022). Again, binder jetting and selective laser sintering could be used for rigid packaging forms such as containers or trays. These techniques enable complex shapes and features, for example, compartments or sealing mechanisms. Scientists have created thin, flexible films from orange peels and banana skins (Nida et al., 2022). Nida et al. (2022) claimed that the films have outstanding barrier properties against oxygen and moisture, which makes them suitable for perishable food products. Chitosan containers from seafood shells have been developed to create rigid, compostable containers for dry goods (Xia et al., 2024). Such containers decompose rapidly under natural conditions, which reduces environmental impact. Composite multi-layer packaging could also be created by combining starch-based layers with protein-based coatings using 3D printing, with enhanced strength and resistance to degradation. These 3D-printed packages are feasible and economically viable because they decrease raw material costs while increasing the revenue generated for food processors. It also caters to the increasing consumer demand for environmentally friendly products, giving a competitive advantage in the market.

Furthermore,3D printing allows for the creation of highly customized packaging solutions, including personalized shapes, sizes, and functionalities such as resalable openings or enhanced grip. Despite its potential, several challenges must be addressed to scale up the production of biodegradable packaging. Food waste-derived materials often have variable compositions, affecting printability and mechanical properties. Standardizing the pre-processing steps is critical (Tonini et al., 2018). While biopolymers are biodegradable, they often lack the strength and durability of traditional plastics. Further research into additives and composite formulations is required to enhance these properties. Although biodegradable packaging is sustainable, it is still more expensive than petroleum-based plastics. Economies of scale and efficient supply chains can help bring down the costs (Iftekar et al., 2023; Nazir et al., 2023). In addition, packaging materials intended for food contact must meet stringent food safety standards, which may require extensive testing and certification. Fig. 7 illustrates the diverse applications of 3D printing in food waste upcycling, showcasing its role in creating value-added products, such as customized foods, biodegradable packaging, and edible coatings, thereby promoting sustainability and innovation in the food industry. Table 3 summarizes the uses of different food wastes and by-products via 3D printing, including their ingredients, processing parameters, and significant outcomes in the context of transforming waste into novel, high-value products.

Consumer perceptions and market dynamics

The success of 3D-printed food products made from waste streams depends heavily on the interplay between consumer acceptance, market readiness, and regulatory frameworks. Consumer acceptance of 3D-printed food made from food waste is influenced by several factors. Consumers increasingly value eco-friendly products, recognizing the role of food waste valorization in reducing environmental impact. Functional foods enriched with fibres, vitamins, and antioxidants from food by-products attract health-conscious buyers. The ability to personalize food in terms of flavor, nutrition, and aesthetics appeals to modern consumers (Chang et al., 2024). However, there are some psychological barriers too. Associating food products with “waste” can create resistance. Effective communication and branding are critical to overcoming this challenge. Ensuring waste-derived materials are free from contaminants and safe for consumption and clear labelling of food sources and processing methods is essential to gain consumer trust. Then technological skepticism like the idea of consuming 3D-printed food may seem unnatural to some consumers, requiring education about the safety and benefits of the process. Several researchers like Tonini et al. (2018); Jagadiswaran et al. (2021) claimed that food manufacturers adopting these solutions will have waste management cost savings of up to 25 %. But over everything, consumers firstly prioritize taste, texture, and appearance. Successful 3D-printed products must align with traditional sensory expectations while offering unique value.

However, 3D-printed foods provide multiple allergenicity risks, such as cross-contamination with allergens, ingredient substitutions, and invisible allergens. Material handling, public nozzles, and extruders, along with alternative binders, may introduce latent allergens as discussed in the study of Tran (2019). Regulatory standards for allergen labelling in 3D-printed foods are still developing, resulting in a deficiency in consumer awareness and safety, especially for those with severe allergies. Heavy metal contamination in 3D food printing can happen because of using stainless steel or brass nozzles, certain food-safe materials, and high temperatures during printing. Extended exposure to lead and cadmium can result in neurotoxicity, renal failure, and developmental disorders, particularly in children (dos Santos et al., 2022). Nickel and chromium can cause allergic reactions and gastrointestinal problems, especially in individuals with metal sensitivity. To avoid heavy metal contamination, you can use safe food-grade nozzles, test and certify for metal contamination, and improve printing settings. Transitioning to ceramic- or titanium-based nozzles reduces the risk of heavy metal leaching (dos Santos et al., 2022). Consistent assessments of 3D-printed food substances ensure adherence to food safety regulations like HACCP, EFSA, and FDA guidelines for upcycled food products.

Several regulatory frameworks and government initiatives worldwide support food waste valorization and sustainable food processing technologies like 3D printing. In India, the Food Safety and Standards Authority of India (FSSAI) has launched the Save Food, Share Food, and Serve Food Initiative, which promotes waste reduction and food redistribution (Tran, 2019). Additionally, the National Bio-Energy Mission encourages the utilization of agricultural and food waste for value-

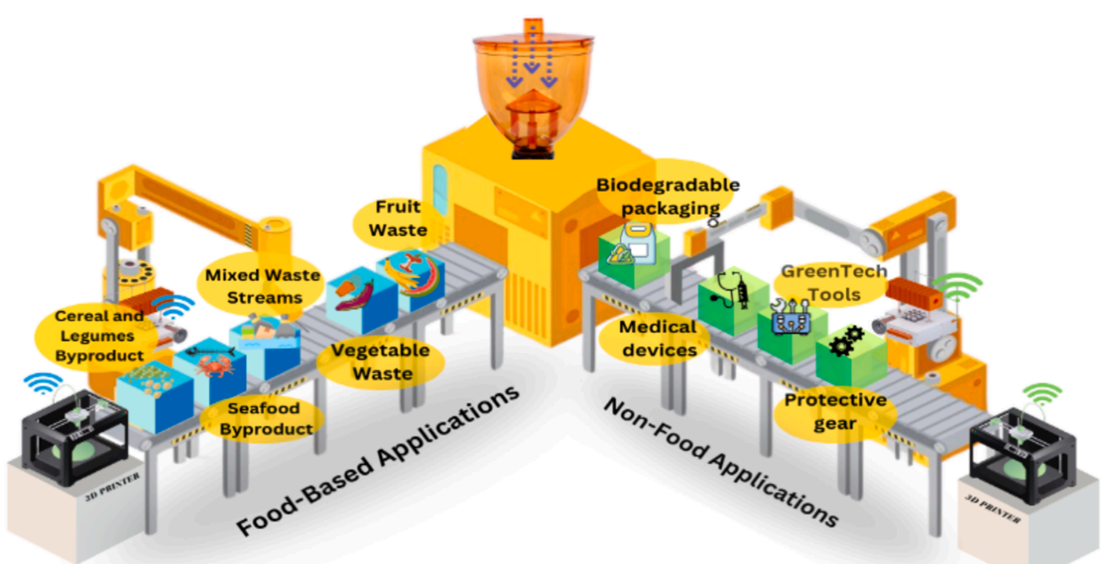


Fig. 7. Applications of 3D printing in food waste upcycling.

Table 3
Utilization of various food wastes and by-products using 3D printing.

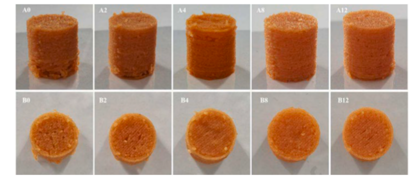
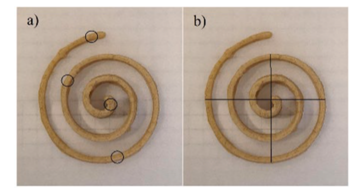
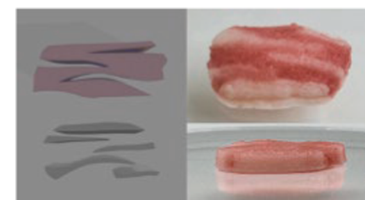
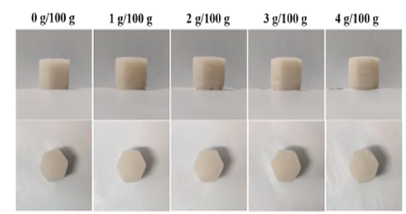
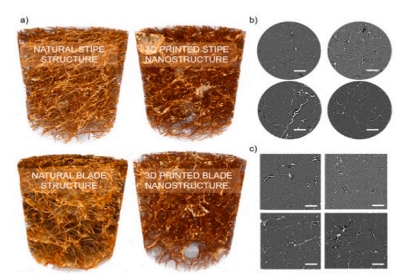
3D Printed Product	Food Waste Utilized	Other Ingredients/ additives	Printing Technique	Printing/ Processing Parameters	Post-Printing Treatments	Key Findings	Figures/ block diagram	Ref
Carrot pulp cylinders	Carrot pulp	Potato starch, xanthan gum	Extrusion-based printing	Nozzle: 0.8 mm; Temp: 90 °C; Speed: 25 mm/s	Cooling and setting	Particle size reduction increased apparent viscosity, printing stability, cohesiveness and gumminess and carotenoid release		(Feng et al., 2021)
Functional dough/ baked snack	Wheat and amaranth bran	Oat flour, rice proteins, sunflower oil; salt, baking powder	Extrusion-based printing	Nozzle: 1 mm; Temp: 20 °C; Speed: 25 mm/s	Baking (140–160 °C for 18 min)	Reduction of Fructan levels; bran bioprocessing increased printing precision by 13 %, increased viscosity and yield stress		(Habuš et al., 2021; Habuš et al., 2022)
Protein-based hydrogel rich printed food	Pumpkin seeds	Alginate, gelatin NaOH	Hydrogel forming extrusion	Pressure: 175 kPa; Needle diameter: 510 µm; Speed: 4 mm/s	–	Developed hydrogel mimics gelatin's appearance and texture; improved crystallinity and structural integrity; precise customization		(Kong et al., 2024)
Low-salt surimi gel	Micron fish bone	Northern pike fish meat, scales, urea	Hydrogel forming extrusion	Temp: 25 °C; Nozzle: 1.2 mm; Layer height: 1.1 mm; Infill: 100 %; Speed: 15 mm/s;	Cooking (water bath at 40 °C for 60 min and then at 90 °C for 30 min)	Unrolling of the surimi protein structure; covalent crosslinking within protein molecules		(Wei et al., 2024)
Hybrid hydrogels	Brown seaweed residues	Deionized water	Pneumatic-based extrusion bio-printing	Nozzle: 0.5 mm; Pressure: 5 kPa;	Cross-linking using $CaCl_2{\cdot}2H_2O$ for 30 min	High cellulose content; inks displayed excellent shear-thinning behaviour, cytocompatibility; favourable mechanical properties, and a cell viability of 71 %		(Berglund et al., 2020)

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Table 3 (*continued*)

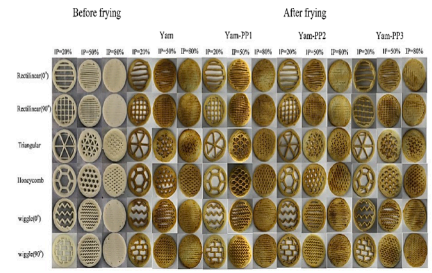
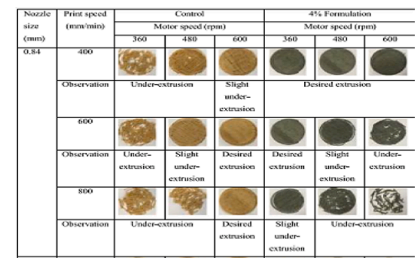
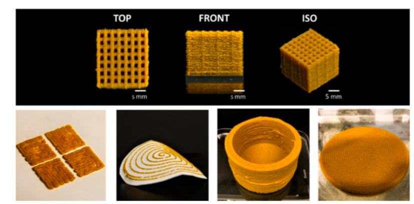
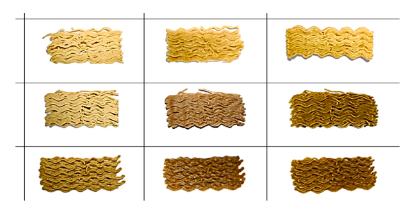
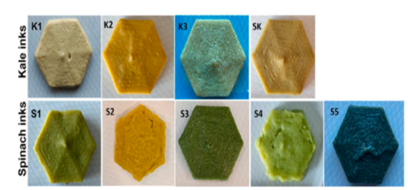
3D Printed Product	Food Waste Utilized	Other Ingredients/ additives	Printing Technique	Printing/ Processing Parameters	Post-Printing Treatments	Key Findings	Figures/ block diagram	Ref
Yam Snack	Potato processing by-product	Freeze dried yam, hot water at conc. 400 g/L	Extrusion-based	Nozzle: 1.2 mm; Layer height: 1.2 mm; Speed: 20 mm/s; Extrusion rate: 22 mm^3/s; Infill: 20 %, 50 % & 80 %	Freezing (−20 °C for 24 h); air frying (100, 130 & 160 °C for 12, 16 & 24 min.)	Hardness after air-frying decreases with porosity; swelling ratio range: 1.18 ± 0.07 to 1.20 ± 0.09; swelling ratio affected by viscosity and volume flow, height deformation reduced.		(Feng et al., 2020)
Functional cookies	Grape pomace	Wheat flour, powdered sugar, margarine, baking soda, water	Extrusion −based	Temp: 25 ± 3 °C; Nozzle: 0.84 mm, 1.28 mm; Speed: 400 mm/min, 600 mm/min, 800 mm/min;	Baking (130 °C for 12 min); cooling (room temp. for 10 min)	Product rich in protein and dietary fibre; grape content increased viscosity; baking impact shape and structural stability.		(Jagadiswaran et al., 2021)
Nutritious snack	Orange peel waste (OPW)	Deionized water	Direct ink writing (DIW)	Syringe: 50 mL; Nozzle: 20G*; Speed: 50 mm/s; Pressure: 0.090 Mpa; Layer height: 0.40 mm	Setting and cooling	OPW exhibited shear thinning behaviour for easy extrusion; printed structure didn't spread post printing		(Leo et al., 2022)
RTE noddles	Potato peel waste	Guar gum, whole wheat flour, table salt, vegetable oil,	Cold Extrusion-based printing	Nozzle: 1.28 mm; Pressure: 6 bar; Speed: 600 mm/ min; motor speed: 600 rpm	Steaming (5 min); drying (68 °C, 2.5 h)	Fine particles below 0.125 mm size exhibited smooth material flow; fair sensory acceptability, higher cooking time, higher solid gruel loss		(Muthurajan et al., 2021)
Dysphagia foods	kale stalks and spinach stems (steamed & boiled)	Potatoes, corn starch, agar, gelatin, spinach and mushroom paste, pumpkin, honey, charcoal pills	Extrusion-based printing	Nozzle: 1.5 mm; Speed: 3500 mm/ min; Layer height:1.4 mm;	Setting and cooling	Kale inks printed well with uniform and smooth extrusion and showed little water spread; spinach ink poorly printed due to high moisture.		(Pant et al., 2023)

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Table 3 (*continued*)

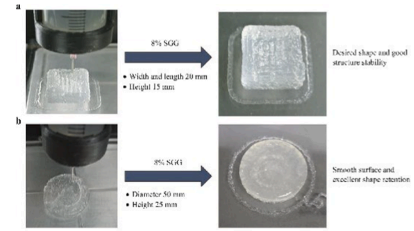
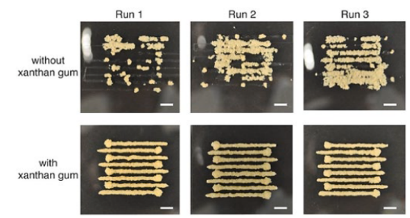
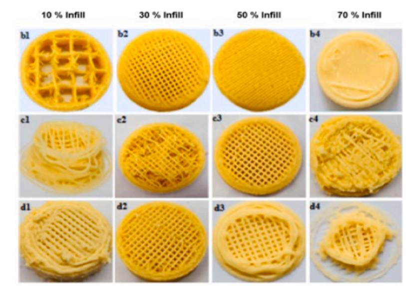
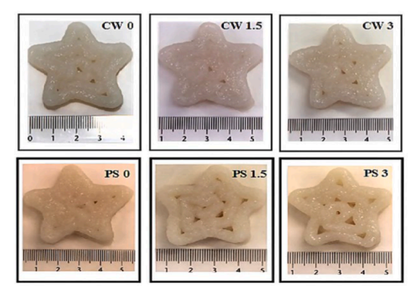
3D Printed Product	Food Waste Utilized	Other Ingredients/ additives	Printing Technique	Printing/ Processing Parameters	Post-Printing Treatments	Key Findings	Figures/ block diagram	Ref
Salmon-gelatin cubes	Salmon skin gelatin	Distilled water –	Hydrogel forming extrusion	Nozzle: 0.7 mm; Temp: 15 °C; Layer height: 0.5 mm; Speed: 20 mm/s	Cooling (24 h at a temp. 7 ± 2 ∘C)	SGGs exhibited shear thinning and viscoelasticity (mostly elastic); 8 % SGG have greater dimensional stability		(Carvajal-Mena et al., 2022)
Okara snack	Okara (Soybean by-product)	Distilled water	Direct ink writing	Nozzle: 1.5 mm; Speed: 30 mm/s; Infill: 25 %, 50 % and 100 %	–	High-protein content; consistent layer-by-layer adhesion at 33 % w/w conc.;		(C. P. Lee et al., 2021)
Cookies	Dietary fibre from okara	Wheat flour, butter, powdered sugar, and milk	screw pneumatic linkage extrusion	Nozzle: 0.8 mm; Speed: 50 mm/s; Temp: 25 °C; Infill:10 %, 30 %, 50 %, 70 %	Baking	Fibre rich snacks; addition of 6 % okara fiber with 30 % infill rate- superior printability		(Liu et al., 2021)
Surimi	Cod by-product mince	Salt (NaCl)	Extrusion-based printing	Nozzle: 4 mm; Temp: 25 °C.	Steam cooking (20 min at 90 °C), refrigeration and setting (overnight)	Salt-induced myofibrillar swelling of proteins improved printability; gelling effect also visible.		(Gudjónsdóttir et al., 2019)

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Table 3 (*continued*)

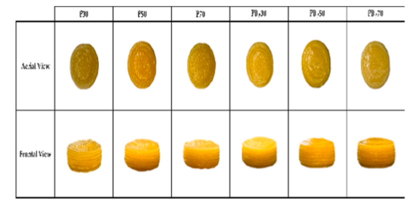
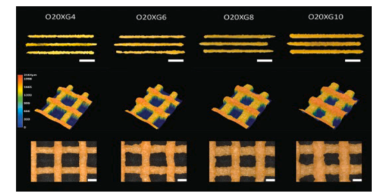
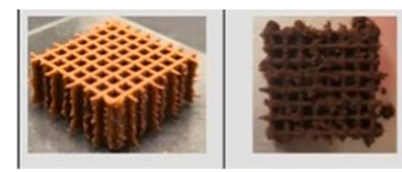
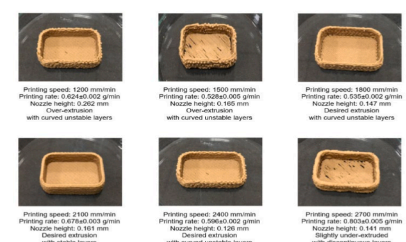
3D Printed Product	Food Waste Utilized	Other Ingredients/ additives	Printing Technique	Printing/ Processing Parameters	Post-Printing Treatments	Key Findings	Figures/ block diagram	Ref
Apricot gel snacks	Orange zest	Bovine gelatin, apricot pulp,	Fused Deposition Modelling (FDM)	Temp: 25 °C; Nozzle: 1.2 mm; Speed: 20 mm/s; Layer height: 1.2 mm; Rectilinear infill: 100 %	Freezing (24 h at − 45 °C); Freeze drying (48 h at 2600 Pa and − 56.6 °C)	Orange zest addition increased elasticity and improved printability; Crisp texture after drying		(Molina-Montero et al., 2023)
Healthy snacks	Orange peel waste	Xanthan gum, deionised water	Pneumatic extrusion-based Direct ink writing	Nozzle: 20G; Syringe: 50 mL; Speed: 30 mm/s; Pressure: 0.160 Mpa; Layer height: 0.40 mm	Oven Drying (180 °C for 8 min)	DIW printing had no effect on the bioflavonoids and antioxidants, OPW did not exhibit cytotoxicity		(Da Tan et al., 2023)
Functional food	Durian husk	Deionized water; Xanthan gum	Pneumatic extrusion-based DIW printing	Nozzle: 16G, 20G; Syringe: 50 mL; Speed: 20 mm/s; Room temp.	–	Reducing particle size improved printing; xanthan gum addition reduced the zero-shear viscosity and yield stress		(Da Tan et al., 2022)
Food packaging container	Rice Husk	Guar gum	Extrusion-based printing	Nozzle: 0.82 mm; Motor speed: 300 rpm; Speed: 2100 mm/min; Pressure: 4 bar; Nozzle height: 0.2 mm; Temp: 25 °C	–	Size reduction affected printability; biodegradable; retains shape after filling		(Nida et al., 2021)
Food Packaging	Sugarcane bagasse and banana peel	Guar gum	Extrusion-based printing	Nozzle: 1.2 mm; Pressure: 3.2 bar; Motor speed: 240 rpm; Speed: 500 mm/min,;	–	Rich in cellulose, hemicellulose and lignin-high structural stability.		(Nida et al., 2022)

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Table 3 (*continued*)

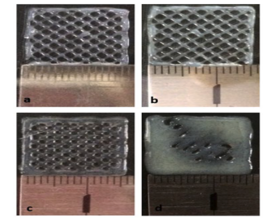
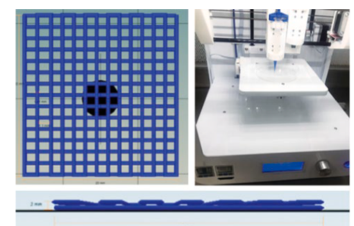
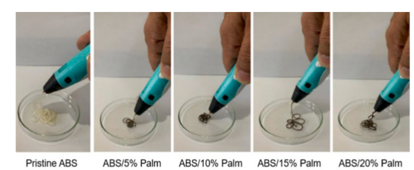
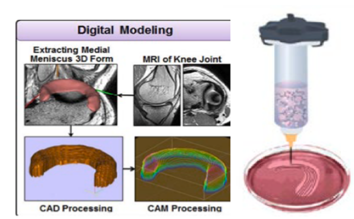
3D Printed Product	Food Waste Utilized	Other Ingredients/ additives	Printing Technique	Printing/ Processing Parameters	Post-Printing Treatments	Key Findings	Figures/ block diagram	Ref
Collagen-based scaffold	Eel fish skin waste	Sodium alginate	Hydrogel forming extrusion	Syringe: 10 mL; Pressure: 20 kPa; Nozzle: 26G;	Cross-linking with 100 mM CaCl2 solution	Hydrogels with collagen show enhanced metabolic activity like higher swelling; excellent biocompatibility		(Govindharaj et al., 2019)
Nono hydroxyapatite scaffolds	Cuttlefish bones, mussel shells, chicken eggshells	chloroform	Hydrogel forming extrusion	Temp: 90–150 °C; Pressure: 4 bar; Speed: 2.5 mm/s; Nozzle: 600 μm	–	Scaffolds possess improved mechanical properties and enhanced bioactivity		(Cestari et al., 2021)
Hydrogel scaffold	Lizardfish scale waste and sea weed	Alginate (extracted from brown algae), $CaCl_2$ (cross-linker)	DIW printing	Temp: 25 °C; Nozzle: 0.644 mm; Speed: 5 mm/s; Infill: 100 %;	–	Biocompatible and non-toxic; high printing accuracy (97 %); 538 % swelling ratio, and 133 kPa of compressive strength		(Boonyagul et al., 2022)
Fibre rich Polymer filament composites.	Palm residues	Acrylonitrile butadiene styrene (ABS)	3D printing pen	–	–	Filaments had good appearance, shape, and mechanical stability		(Marton et al., 2022)
Hybrid polymer composites	Walnut and eggshell powders (bio fillers)	PLA, sodium alginate, deionized water	Hydrogel forming extrusion	Nozzle: 0.4 mm; Layer Height: 0.3 mm; Infill: 10–30 %; Speed: 60 mm/ s, Temp.: 50–70 °C; Pressure: 20 kPa	Drying and crosslinking	Improved mechanical properties like elongation, elasticity etc; density and melting point of filament increased		(Lohar et al., 2022; Narayanan et al., 2016)

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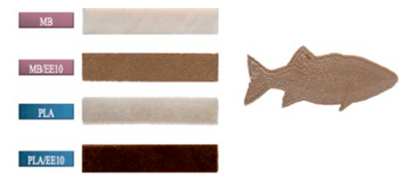
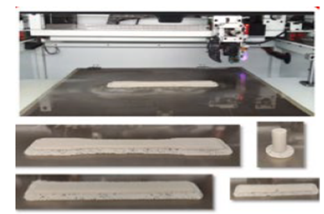
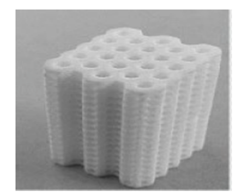
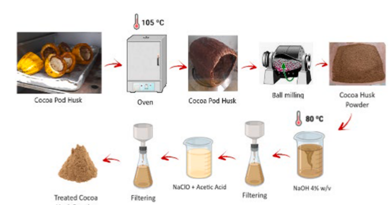
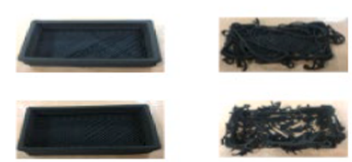
Table 3 (*continued*)

3D Printed Product	Food Waste Utilized	Other Ingredients/ additives	Printing Technique	Printing/ Processing Parameters	Post-Printing Treatments	Key Findings	Figures/ block diagram	Ref
Green composite filaments	Anchovy fish bone waste	PLA and Mater- Bi® EF51L (MB) polymers	Fused Deposition Modelling (FDM)	Temp: 60 °C; Nozzle: 1.75 mm; Rectilinear Infill: 80 %; Speed: 45 mm/s; Layer height: 0.1 mm	Oven Drying (100 °C for 30 min)	10 % incorporation showed outstanding printability; improved flexural modulus; residual fish oil acted as plasticizer		(Scaffaro et al., 2022)
Bio-composite filament	Crab shell	PLA polymeric granules,	FDM method	Speed: 40 mm/s; Temp: 180 °C; Speed: 20 mm/s, Infill: 100 %; Layer height: 0.1 mm	–	Better tensile and flexural strength; suitable for making bio-polymeric components		(Palaniyappan et al., 2024)
Bio-composite scaffold	Shrimp shell	Hydroxyapatite (Hap) suspension	Selective Laser Sintering (SLS) process	Temp: 200 °C; Sinters width: 0.5 mm; Beam speed: 1600 m/s at 45° build direction	–	Suitable for biomedical application; honey comb model gave superior printability results		(Pradeep et al., 2022)
Bio-composite filaments	Cocoa bean shell waste	PLA pellet	Fused filament fabrication (FFF)	Extrusion temp: 200 °C; Speed: 50 mm/s; Infill: 100 %; Fan speed: 100 %.	Cooling and solidification	Satisfactory printability achieved; improved stiffness and load resistance; sensory properties retained.		(Fico et al., 2024)
Cellulose reinforced bio-composite filaments	Cocoa pod husk	PLA granules	Fused Filament Fabrication (FFF)	Nozzle: 0.40 mm; Temp: 180 °C; Speed: 40 mm/s; filament diameter: 1.75 mm	–	Around 18 % improvement in filament tensile strength		(Almeida et al., 2024)
Food package casing	Banana peel waste	Guar gum	Extrusion based printing	Syringe: 30 cc; Pressure: 6 bar; Motor speed: 150 rpm; nozzle: 1.2 mm; Speed: 400, 500, 600, 700 mm/min	–	Unique customized casing; printability greatly affected by particle properties and hydrocolloid conc., alternative to petroleum-based palstics		(Nida et al., 2023)

*G: Birmingham Gauge; RTE: ready-t-eat; SGG: salmon gelatin gel; DIW: Direct ink writing; OPW: orange peel waste; PLA: polylactic acid (a thermoplastic material; FDM: fused deposition modelling;

added applications. Globally, the European Union's Farm to Fork Strategy and Waste Framework Directive (2008/98/EC) emphasize circular economy approaches, supporting innovations in food waste upcycling (De Pascale et al., 2023). The United States Food and Drug Administration (FDA) regulates food processing technologies under the Food Safety Modernization Act (FSMA) to ensure compliance with safety standards in novel food production, including 3D printing (Tran, 2019). Similarly, China's Food Waste Reduction Action Plan and Japan's Food Recycling Law mandate sustainable waste management practices, encouraging businesses to adopt waste conversion technologies. These regulatory efforts create an enabling environment for industries to leverage 3D printing for food waste utilization, ensuring safety, sustainability, and economic viability in food processing innovations.

The market for 3D-printed food products is evolving, with significant interest from sustainability-focused industries and niche consumer segments. Restaurants and food innovators are exploring 3D printing to create customized dishes with unique designs; pioneering gourmet and specialty food markets (Yoha & Moses, 2023). Products offering specific health benefits, such as high-fibre or antioxidant-rich snacks, are gaining traction. However, certain commercialization challenges like extensive initial costs for 3D printing equipment and material preparation can hinder scalability. Maintaining the structural integrity of printed foods during transport requires specialized packaging and logistics (Padhiary, Barbhuiya, et al., 2024). As technology advances, production costs are expected to decline. The major growth drivers, in this case, are proper awareness, technological advancements for high-end products, and support from food industries, emerging start-ups, and other stakeholders who can enhance credibility and facilitate market entry. Also, government policies, subsidies, and incentives for promoting waste valorization and sustainability can offset initial costs.

Challenges and future perspectives

The adoption of 3D printing for food waste valorization offers transformative potential but faces significant challenges and limitations across technical, regulatory, and economic dimensions. Overcoming these hurdles is essential to achieving widespread application and acceptance. The prime technical challenge faced in 3D printing is maintaining consistency in print quality that, in turn, is greatly determined by factors like material variability, texture and stability, and layer adhesions. High-moisture materials, such as fruit peels or vegetable scraps in varying compositions, are extremely difficult to print. In addition, uniform adhesion of the layers is a challenge with fibrous or coarse waste streams. The behaviour of the material during printing, especially flow properties and thermal sensitivity, also poses very serious limitations. For example, materials with improper viscosity may block nozzles or fail to extrude. While heat-sensitive components like proteins and starches can deteriorate during the printing process and alter texture as well as nutritional quality, stabilization through post-printing operations, such as drying, cooking, or setting, can lead to shrinkage, deformation, or a loss of nutritional value. Additionally, scalability in post-processing for mass production remains a challenge. Table 4 illustrates some of the technical challenges that this technology faces, and it also lists a few proposed solutions.

Table 4
Challenges and solutions in 3D printing food waste-based products.

Challenge	Details	Proposed Solution	Ref
Material consistency	Variability in composition of food waste	Pre-processing standardization and formulation control	(C. P. Lee et al., 2021; Liu et al., 2019)
Printability issues	Inconsistent extrusion due to poor flow properties	Use of binders, stabilizers, and rheology modifiers	(Sharma et al., 2024)
Structural instability	Lack of strength in printed objects	Layer-by-layer optimization and post-processing	(Pradhan et al., 2024)
Limited shelf life	Products degrade quickly due to natural components	Incorporation of natural preservatives	(Leo et al., 2022)
Scaling up production	Limited throughput in 3D printing	Parallel printing systems and automated workflows	(Padhiary, Barbhuiya, et al., 2024)
Cost of 3D printers	High initial investment	Subsidies, leasing programs, or open-source printers	(TAPIA & SANCHEZ, 2024)
Regulatory hurdles	Food safety compliance requirements	Conducting extensive safety testing and certifications	(Iftekar et al., 2023)
Consumer acceptance	Skepticism towards waste-based foods	Awareness campaigns and sensory quality improvements	(Iftekar et al., 2023; Nazir et al., 2023)
Material drying issues	Moisture content impacts printability	Pre-treatment techniques like freeze or spray drying	(Nida et al., 2022)
Limited nutritional customization	Generic formulations	AI-driven optimization for nutrient-rich recipes	(Elbadawi et al., 2024)
Biodegradable packaging durability	Low mechanical strength	Addition of nanomaterials for reinforcement	(Almeida et al., 2024)
Ingredient sourcing	Irregular supply of food by-products	Building localized supply chains	(Shanmugasundaram et al., 2020)
Energy consumption	High energy demands of 3D printers	Use of energy-efficient hardware	(Nazir et al., 2023)
Post-printing requirements	Time-intensive stabilization steps	Developing faster curing or setting methods	(Kadival et al., 2023)
Consumer pricing concerns	Higher costs of 3D-printed products	Economies of scale and demand-driven cost reduction	(Padhiary, Barbhuiya, et al., 2024)

Cost Economics of 3D Food Printing: 3D food printing offers cost-effective solutions for traditional food processing by reducing raw material costs, energy consumption, and operational costs. Traditional methods discard a significant percentage of food waste, but 3D printing repurposes food waste into printable food inks, reducing costs by 20–40 % (Kadival et al., 2023). This eliminates additional costs for protein fortification. 3D printing operates at controlled temperatures, reducing energy consumption by up to 30 % compared to traditional methods like baking, frying, and extrusion. This results in a 40 % energy reduction. On-demand, localized 3D food printing reduces the need for long-distance supply chains, reducing transportation expenses by 25–35 % (Kadival et al., 2023). For instance, a study found that on-site 3D-printed plant-based meat production in restaurants reduced logistics costs by 30 % compared to bulk-shipped frozen plant-based patties (Wang et al., 2022). Overall, 3D printing offers a more efficient and cost-effective alternative to traditional food processing methods.

***Environmental impacts of 3D Food Printing*:** 3D food printing can significantly reduce carbon footprints by optimizing waste utilization and enabling localized production, reducing emissions by up to 50 % in certain food sectors. For instance, 3D-printed alternative protein sources emit up to 90 % less CO_2 compared to traditional meat processing (Wang et al., 2022). Additionally, 3D printing can transform food waste into valuable products, reducing disposal costs and landfill accumulation. For instance, upcycling vegetable peels into 3D-printed nutrient-rich snacks reduces organic waste disposal by 30–40 % in food processing industries (Majerska et al., 2019). 3D printing is an additive process, requiring only the necessary materials and reducing reliance on artificial additives and preservatives. For instance, 3D-printed biodegradable food packaging from food waste-derived biopolymers reduces plastic waste generation by 50–60 % in sustainable packaging initiatives (Nida et al., 2022).

Hurdle technologies

Hurdle technologies combine multiple non-thermal processing methods to enhance food safety, quality, and shelf life while preserving nutritional value. The integration of these methods with 3D printing addresses several challenges related to the use of food waste materials. Hurdle technologies such as ultrasound-assisted printing have been reported to improve food safety and shelf life due to microbial cell membrane disruption by acoustic waves, even without the drawback of heat on sensitive components (Gu et al., 2024). Additionally, the integration of ultrasound and 3D printing can enhance the rheological properties of waste-derived materials, making them appropriate for printing. HPP-assisted printing may help stabilize food waste materials so that the quality of prints will be consistent while the safety of the final product will be enhanced (Gulzar et al., 2023). Other non-thermal technologies, including pulsed electric fields and ohmic heating, may be used to further improve the material properties and safety of food waste before printing, retaining the nutritional and sensory attributes of food waste-derived ingredients (Shen et al., 2023). By optimizing the material properties, the possible types of food waste to be used in 3D printing expand with hurdle technologies.

AI/ML integration

Through integration with artificial intelligence (AI) and machine learning (ML), several avenues will significantly enhance the efficiency and effectiveness of 3D printing in food waste valorization. The algorithms can process large datasets for the identification of optimal formulations of food waste materials to improve their texture, flavor, and nutritional content (Elbadawi et al., 2024). Algorithms can be designed to create customized blends of food waste, making sure that they contain the right ingredients for specific printing properties. In addition, ML-based models can be used to predict the printability of different materials based on physicochemical properties, thus enhancing rapid prototyping and testing (Padhiary et al., 2023; Padhiary, Saha, et al., 2024). Understanding how a material behaves while printing allows a manufacturer to choose the right pre- and postprocessing techniques and also the printing parameters. ML models like the Relative Least General generalization algorithm can be efficiently used for predicting the relationship between the mechanical properties of ink and printability, particularly for Type-I collagen-based prints (J. M. Lee et al., 2021). Bone et al. (2020) utilized Hierarchical machine learning for optimizing print fidelity of sodium alginate for iterative proof reduction. Similarly, other researchers like Jin et al. (2021); Ruberu et al. (2021) employed algorithms like Convolutional Neural Networks (CNN); Deep Neural Networks (DNN) and Bayesian optimization in the printing of materials like Gelatin methacrylate, alginate, a mix of gelatin methacryloyl and hyaluronic acid methacrylate. The algorithms proved to be effective in anomaly detection and prediction, print quality prediction and optimization, etc.

AI can analyse waste streams, identifying trends and patterns that will help separate and process better. Machine learning algorithms can optimize the supply chain in the food chain, helping manufacturers to source and process food waste better, and boosting printability by 15–20 % (Elbadawi et al., 2024; Prasad et al., 2025). Even more advanced algorithms enable the production of customized food products tailored to the consumer's needs and preferences: dysphagia foods, space foods, etc. AI-powered computer vision systems combined with IoT sensors can track and correct defects in real-time, resulting in a 25–40 % reduction in print failures and reduced material wastage (Bedoya et al., 2022). AI can also process consumer preference data to create customized 3D-printed food products tailored to nutritional needs and taste preferences. For example, AI can analyse consumer dietary preferences and recommend alternative waste-based ingredients, improving consumer acceptance scores by up to 18 % in taste tests compared to generic formulations (Bedoya et al., 2022; J. M. Lee et al., 2021).

Integration with blockchain technology

Blockchain or Distributed Ledger Technology (DLT) is a decentralized and distributed platform consisting of cryptographically encrypted data termed as blocks, linked together to form a peer-to-peer (P2P) network leveraged to achieve authorization, accountability, authentication, integrity, security, privacy, confidentiality and non-repudiation for real-time applications as in food and food waste traceability (Puthenveettil & Sappati, 2024). Programmable blockchains or smart contracts are computerized transaction protocols executing the terms of a contract automatically upon fulfilling the necessary predefined input conditions without the involvement of intermediaries. The contractual clauses, once finalized and agreed upon by the involved stakeholders are converted to suitable program logic and according to the programming style adopted by the blockchain network, these logical connections are preserved and execute the terms of the contract upon fulfilling necessary criteria or conditions set in the code logic. An important feature of smart contracts is the fact that once the contract is finalized and deployed on the blockchain network, it is immutable and no further changes to the deployed contract can be made. Thus, it offers a robust and flexible tracing mechanism for application to broad categories and a wide variety of food products, with different physical and chemical parameters constantly monitored for safety, shelf life, and food and nutritional content.

Blockchain can document the journey of food waste from source to final product, ensuring full transparency regarding material origins and processing methods (Puthenveettil & Sappati, 2024). This traceability can help to identify the particular sources of any problems (e.g., contamination) in the supply chain and enable rapid responses to food safety concerns. For instance, Tsang et al. (2019) proposed a blockchain-based food quality traceability prototype that embeds a Food Quality Index (FQI) algorithm. This system collects and organizes data coming from various stakeholders along the food supply chain. Then, after processing the data coming from the diverse stakeholders along the food supply chain, the FQI algorithm assesses food quality based on storage and handling laws at the local level, according to food safety regulations. The algorithm provides a value of FQI that decides if the food product passes the safety parameters or not. It will lie within the accepted range for safe consumption. The authors claimed that transparency could be ensured through a public blockchain and specified that shelf life is an important parameter in this research.

Kamath (2018) mentions Walmart's pilot program with regard to the mango supply chain through IBM's usage of the Hyperledger blockchain. The pilot tracked, in cross-border trade mango slices, maintaining high-quality produce from farms to retail shelves while advocating the application of blockchain to quality assurance and traceability. Likewise, it can build trust and acceptance by providing consumers with access to detailed information about the sourcing and processing of 3D-printed food products (Padhiary, Saha, et al., 2024). Labels that integrate blockchain technology can inform consumers about the environmental impact of their purchases, appealing to eco-conscious buyers. Blockchain can enable collaboration among various stakeholders in the food supply chain, including farmers, processors, manufacturers, and retailers (Puthenveettil & Sappati, 2024). Smart contracts can automate transactions and ensure that all parties adhere to agreed standards and practices, enhancing efficiency.

Nanotechnology integration

Nanotechnology can greatly advance 3D food printing and the development of sustainable materials by enhancing the functional, mechanical, and interfacial properties of materials derived from food waste. Nanocellulose, derived from plant materials or agricultural residues, exhibits high tensile strength, lightweight properties, and biocompatibility, which enable long-lasting 3D-printed structures (Yadav et al., 2021). Nanoclays are silicate layers at the nanoscale and are great insulators, reducing permeability to oxygen and water vapor, extending the shelf life of biodegradable packaging or edible films (Padhiary et al., 2025). Chitosan nanoparticles are derived from seafood by-products, with structural and antibacterial attributes, which increase food safety and shelf life extension of printed materials (Pradeep et al., 2022). However, there are still issues to address, including the need for enhanced compatibility with food waste streams and regulatory concerns. Nanotechnology in 3D printing combines potential innovations with the symbiosis of nanomaterials with other cutting-edge technologies, such as AI and blockchain traceability. This will improve the efficiency and sustainability of food waste valorization, increase adaptation and flexibility in food systems, and motivate a more sustainable and circular economy.

Conclusion

With over 1.3 billion tons of annual food wastage and food processing industries contributing up to 40 %, 3D food printing technology offers a cutting-edge solution for concerns related to waste streams and by-products. The printing application, with its advantageous high precision, customization, resource utilization, and provision for decentralized productions with enhanced food safety and hygiene; fundamentally aligns with the prospects of circular economy and sustainability. Thus, in order to mitigate the global food crisis, it is crucial and urgent to upcycle nutrient-rich leftovers like fruit peels, vegetable scraps, and seafood shells into value-added goods. This will allow these materials to be 3D printed into nutrient-rich, visually pleasing food products that improve nutritional profiles by 20–35 % and reduce waste by up to 60 %. Additionally, it will meet consumer demand for unique and practical food solutions by permitting mass customization and optimizing waste. Due to advancements in blockchain-based traceability, AI-driven process optimization, and improved printability, food production systems are becoming safer and more dependable by 15 % to 20 %.

Despite these encouraging advances, there are still significant barriers to the widespread adoption of 3D printing in food systems. Further research is needed to overcome issues such as material variability, uniformity, regulatory compliance, and consumer acceptance. In the past, research has primarily focused on enhancing printability and extrusion properties but neglected integration into current food supply chains, scalability, and economic viability. To transcend these barriers and strengthen regulatory frameworks, future research should highly prioritize multidisciplinary cooperation between material scientists, food technologists, and legislators. The use of 3D printing in food manufacturing presents an unprecedented opportunity to transform waste into valuable resources, reduce disposal costs by up to 25 %, and produce products with enhanced functionality and extended shelf life.

CRediT authorship contribution statement

Debapam Saha: Writing – original draft, Investigation, Conceptualization. **Mrutyunjay Padhiary:** Writing – original draft, Visualization, Software, Resources, Formal analysis, Data curation. **Azmirul Hoque:** Writing – review & editing. **Gajendra Prasad:** Validation, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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