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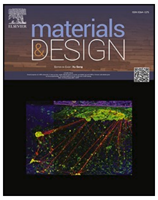

# Upcycling potential of the material extrusion process: a focus on the fused deposition modeling and beyond

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## ABSTRACT

This study reviews the transformability potential of the Material Extrusion (MEX) process as a possible contributor to circular manufacturing by facilitating plastic upcycling and biomass valorization. MEX makes the use of recycled thermoplastics as feedstock and their blending with reinforcement or functionalizing fillers feasible, opening ground-breaking routes to the development of sustainable composite materials. Biomass waste, as filler, can reinforce the thermoplastic matrix but also provide antibacterial, regenerative, and wound-healing properties to the composites. Examples of already developed materials, potential applications, and a focus on four thermoplastic materials (i.e., Polylactic Acid – PLA, Polyhydroxyalkanoates – PHAs, Polycaprolactone – PCL, and Polyvinyl alcohol – PVA) are provided. The discussion focuses on the Fused Deposition Modeling technique and includes the Fused Granulate Fabrication technique. The challenges persisting in material design, fabrication, and printing, limiting functionality and performance, are highlighted to stimulate further research into optimizing all steps of the upcycling process. The contribution of Artificial Intelligence (AI) in pursuing this target, by supporting MEX-related workflows, from optimizing printing parameters and predicting material performance to enhancing the reliability of recycled feedstocks and enabling more effective circular material cycles, is also analyzed.

## 1. Introduction

Strategies for processing and valorizing biomass and waste plastics are continually being evaluated, with multiple scenarios still open [1]. In pursuing this sustainable path, it is key that all envisioned recycling and upcycling solutions are conceived to minimize energy inputs, costs, and environmental impact, thereby truly creating value from waste [2].

Considering the strategic role plastics play in everyday life – being lightweight, cost-efficient, and highly effective – and the current absence of eco-friendly alternatives with comparable performance, a substantial reduction in their use and production is currently out of the question [3]. Treating plastic waste as a valuable resource, being versatile and durable, and not only as a cheap and disposable alternative, in combination with restraining its consumption and promoting long-lasting uses, is fundamental for reducing the plastic footprint [4,5]. A broader perspective is needed, in which the material is considered alongside the entire life cycle and optimized accordingly, and where chemistry and material science can play a primary role [6].

Indeed, conventional recycling methods, including mechanical processes and incineration, are typically categorized as downcycling because the virgin material's initial properties are degraded [7]. However, it is still worth using this plastic waste as a feedstock [8]. An approach to valorize it is to consider plastic upcycling, in which waste plastics are used as feedstock to produce value-added materials and products [9,10]. Upcycling methods that could be pursued towards this target are reviewed in [8,10]; thermal approaches are the most established (even if still less sustainable and energy-intensive [8,11]), and include repurposing, i.e., rethinking and designing novel applications. In such a context, the Material Extrusion (MEX) process [12] and its enabling technologies, such as the Fused Deposition Modeling (FDM) and the Fused Granulate Fabrication (FGF), can actively contribute in the upcycling target [13] also considering that most commodity plastics are thermoplastics that can be melted and reprocessed [14] using both technologies and the increased design freedom allowed by Additive

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Manufacturing (AM); this is also key in promoting new applications.

In addition to thermoplastics, biomass waste management is also a worldwide concern [15,16]. The term "biomass" refers to organic materials derived from organisms, including plants, microorganisms, and animals, as well as by-products from the processing of wood and agro-food sources [17]. Reducing waste and greenhouse gas emissions is a crucial component of sustainability, contributing to the development of a circular economy [18]. As for plastic waste, a strategy to mitigate the consequences of biomass-byproduct generation is to exploit them. Potential uses for biomass currently include the production of biofuels, biogas, and other eco-friendly products that offer sustainable substitutes for fossil fuels [19].

FDM, also known as Fused Filament Fabrication (FFF), uses thermoplastic polymers and thermoplastic-based composites supplied as spools of filament. It is characterized by low initial setup costs and a wide range of commercially available materials and variants [20]. FDM supports control over multiple processing parameters [21], multi-material printing [22], and advanced customization of printing paths [23]. While previously considered only a prototyping technology, it is now also viewed as a manufacturing asset, enabling the fabrication of finished goods [20,24]. There is also a vital academic and industrial interest in exploring new materials, refining printing processes, and addressing scalability challenges [25]. Efforts are also underway to systematize testing procedures [26,27] and ensure that 3D-printed parts meet stringent standards and regulatory requirements [28,29]. With its widespread adoption and broad range of applications, this technology has the potential to shape the future of manufacturing and, consequently, its environmental impact [30]. Its processes typically require lower energy when operated continuously, and pairing with eco-friendly materials could also promote environmental sustainability [31]. Machines often have relatively simple mechanical systems that favor repair strategies. Waste from failed prints or from consumer goods streams can be collected, reprocessed, and reused in future printing cycles [32].

FGF is also an enabling technology for MEX and has demonstrated the ability to successfully process a wide range of materials, including recycled plastics and composites [33–35]. Thanks to a screw-based extruder, this technology enables printing directly from pellets or granules rather than filaments [35]. Although it is still less widely used than FDM, there is growing interest in it [35]. FGF enables more versatile testing of novel material compositions. Biobased materials can be successfully printed [36], as can materials that are instead challenging for FDM, such as low-shore thermoplastic elastomers [37,38] or Polyethylene terephthalate (PET) [39]. With FGF, the time and energy required for filament production are skipped [40]. This step, which is instead necessary for FDM, introduces additional melt and solidification cycles, thereby weakening material properties [34]. A life cycle assessment study comparing FGF, traditional FDM, and injection molding (IM) has demonstrated that FGF has a greater potential to reduce climate impact (measured as $CO_2$-equivalent emissions per functional unit) than FDM (by 82.1 %) and IM (by 70.6 %) [41]. The impact of traditional FDM (i.e., from virgin filaments) stems from material transport (especially in domestic settings, where light commercial trucks are widely used) and from packaging for filament spools [41]. If recycled material is used, the overall impact decreases but remains higher than the FGF [41]. However, while FGF is a reference for producing large-format components (e.g., furniture, molds), the ability to manufacture small-scale details with high resolution and tight tolerances remains limited [13], even though small-scale systems are now available [42] and likely to become more widespread in the future. In addition to FDM and FGF, we can also mention, for example, paste-based technologies, classified under the MEX umbrella, whose interest is rising in the building design and construction field due to their potential to process low-impact, natural materials, even if there are still several challenges to address, including structural and durability issues of the printed artifact [43].

Conscious of the environmental sustainability potential of the FGF technology, we will focus more on FDM in this study because it is still more widely available [44], more affordable, and already has a broader range of applications. Anyway, the FGF will also be part of the discussion. The FGF is a standalone opportunity but also a technology that could be used to, for example, scale up environmentally sustainable FDM-based ideas with appropriate process revisions. Therefore, the general material-level considerations discussed in this study could also be relevant to the FGF. Considering these premises and the role that AM could play in promoting sustainable manufacturing practices, favoring also distributed recycling models [45,46], the point analyzed in this study is understanding what contribution the MEX process and, specifically, the FDM/FGF technologies could provide to the circular economy paradigm from the perspective of thermoplastic waste and biomass upcycling [47].

Several studies have already discussed the environmental sustainability potential of MEX, particularly FDM, and the challenges that remain [13,30,48–50]. Others have explored the concept of upcycling waste and the use of biomass waste in 3D printing [51] and 4D printing [52]. Here, we aim to combine these two aspects, focusing on the upcycling of thermoplastic and biomass waste and emphasizing the role of MEX and its enabling technologies in facilitating this achievement.

MEX can help address the waste management problem by promoting the development of value-added, environmentally sustainable new materials and related applications, by leveraging the integration of recent advancements in waste reprocessing, material design and manufacturing, machine capabilities, design for additive manufacturing [53], and Artificial Intelligence (AI) in a synergistic manner (Fig. 1).

Further deepening this statement holistically remains worthwhile. The availability of affordable desktop-based solutions for printing (especially for FDM and, even more in the future, for FGF) and for raw material manufacturing (for the FDM) has spurred widespread adoption of the MEX process which is crucial for stimulating environmentally sustainable innovations; however, if this innovation is not guided correctly, it could also exacerbate the unoptimized use of materials, introducing further pressure in the management of plastic waste [30,54], which is already challenging considering its wide variability [6]. Often used by amateurs of different ages (from students to adults) as well as professionals, FDM and, in the future, FGF can reach a broad audience that can therefore be trained or become more familiar with environmentally sustainable practices for recycling plastics and biomass.

In this context, AI can also play a significant role. First, it can support the management of material variability at the manufacturing level through process parameters optimization, which is intrinsically linked to the use of recycled raw materials. Second, it can help identify potentially compatible heterogeneous waste that can be processed together. Lastly, AI can enhance recycling workflows in FDM by improving the identification, sorting, and separation of polymer waste streams, ensuring cleaner recycled feedstocks and enabling more reliable circular-material cycles [10].

To explore these aspects, this study begins by setting the stage for FDM and the FGF techniques (**Section 2**) to familiarize readers, even those working in AM but not focused on MEX, with some technical details. Then, it analyzes innovations in raw-material manufacturing and material printing, characterizing the FDM ecosystem to highlight its market dynamics. Four well-known thermoplastic biodegradable polymers, i.e., Polylactic Acid (PLA), Polyhydroxyalkanoates (PHAs), Polycaprolactone (PCL), and Polyvinyl alcohol (PVA), are then analyzed. Their potential role and the challenges they face in contributing to environmental targets are disclosed. Then, MEX-based plastic upcycling solutions are reviewed. The second part (**Section 3**) discusses biomass valorization via MEX. The focus is on the use of biomass as a filler to reinforce the thermoplastic matrix and reduce the amount of virgin plastic used, but also as a source of bioactive compounds to functionalize 3D-printable materials for healthcare applications. The third part (**Section 4**) discusses how AI can enhance MEX's environmental sustainability potential. Finally, **Section 5** ends the paper.

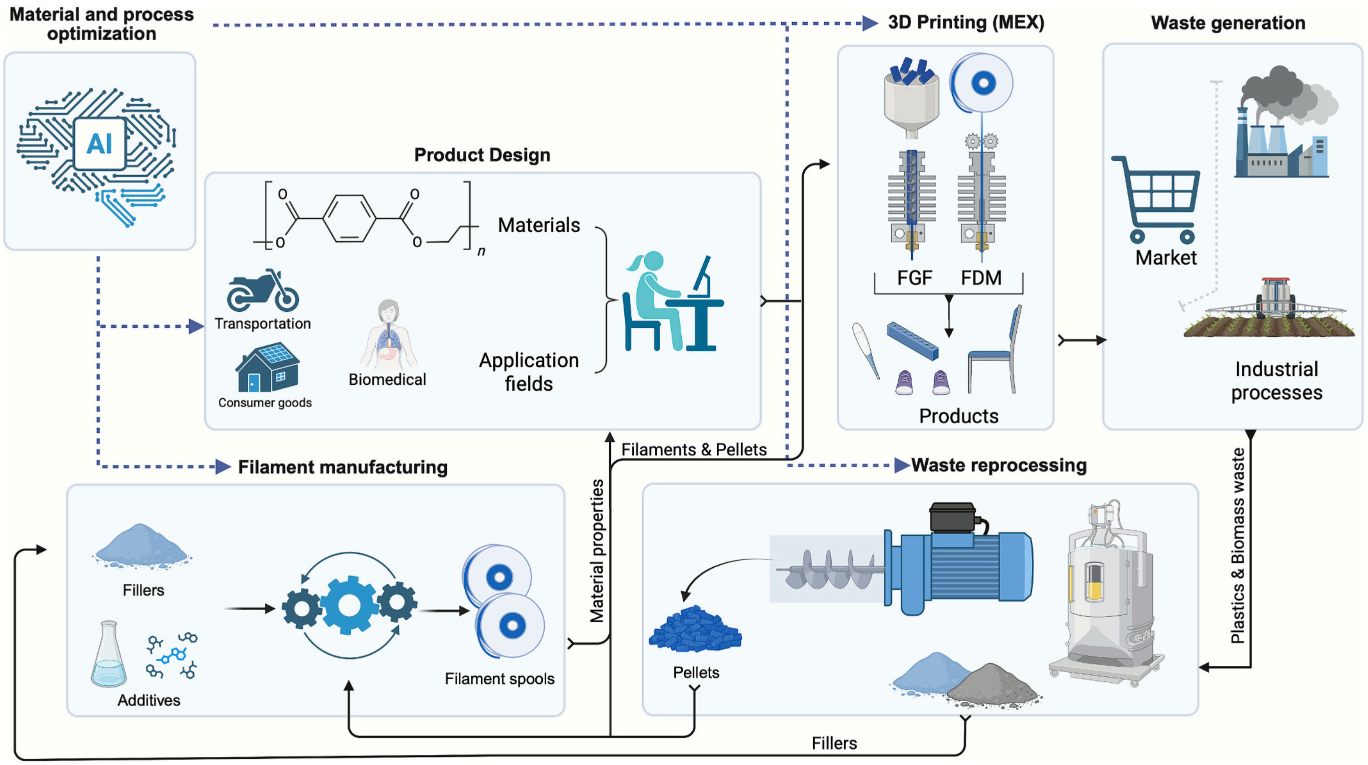

**Fig. 1.** How the MEX process could promote sustainable manufacturing approaches: overview of the main topics discussed in the study. The diagram illustrates how MEX can address plastic and biomass waste valorization by enabling the creation of novel, value-added materials/products through the synergistic integration of advances in waste reprocessing, material design and manufacturing, machine capabilities, design for additive manufacturing, and Artificial Intelligence (AI). The various processes shown in the figure are represented in simplified form. They have been modelled for illustrative purposes and not for providing technical details. Created in BioRender. Graziosi, S. (2026) https://BioRender.com/iw1hil8.

## 2. Background and evolution of the MEX printing process

### 2.1. An introduction to the printing process and related materials

The FDM technique involves heating, melting, and extruding a thermoplastic filament through a nozzle. The nozzle temperature must be carefully controlled, as excessive heat can degrade the material and negatively affect mechanical properties and print quality. At the same time, too little heat can result in poor flow [55]. A gear-driven mechanism, acting on the filament before melting, forces the material through the nozzle, from which it is deposited onto the build platform, which may be heated to prevent warping or improve adhesion.

In contrast, the FGF process directly processes thermoplastic pellets rather than pre-extruded filaments. Pellets are introduced into a hopper and fed into a heated barrel, where a motor-driven screw conveys, compresses, and plasticizes the material through a combination of shear heating and external heating elements [56]. The screw's geometry, comprising feeding, compression, and metering zones, plays a crucial role in ensuring homogeneous melting, degassing, and stable pressure generation before extrusion. Because the melt is produced continuously within the barrel, FGF systems can achieve higher material quantity, support a wider range of polymer formulations, and offer more precise control over melt temperature and viscosity. Once fully molten, the material is pushed toward the nozzle and deposited onto the build platform, as in FDM. However, the larger melt volume and pressure dynamics in FGF often require more robust nozzles, enhanced cooling strategies, and careful tuning of extrusion parameters to ensure dimensional accuracy and interlayer adhesion.

The printed artifact's mechanical properties, printability, and environmental impact are influenced by the raw material used in its production, making its selection essential [57]. Materials can be, e.g., biobased, biodegradable, composites, exhibit high performance (Polyether Ether ketone – PEEK), be flexible at variable shore hardness (e.g., Thermoplastic Polyurethane – TPU), and be biocompatible (e.g., the PCL, which is also biodegradable).

In the FDM, factors such as nozzle diameter and layer height are key, as they directly influence the resolution and surface quality of the finished product and its mechanical properties [58]. Typical nozzle sizes range from 0.2 to 0.8 mm, while layer heights can vary from 0.1 to 0.3 mm. The layer height also depends on the selected nozzle diameter. In FGF, in addition to nozzle size, key parameters include screw diameter, screw length, screw speed, and barrel temperature [35,42,56]. The screw length influences the time the material is exposed to the heating process, and the barrel temperature influences the melt flow speed [56]. In this technology, nozzle diameters can be, for example, smaller than 1 mm in small-scale systems and up to about 10 mm in large-scale systems [42].

The strength of the object depends on the bond between its layers. Layer bonds form as the material cools and solidifies, because the heat from the molten material partially remelts the top surface of the previous layer when a new layer is deposited [58,59]. The cooling rate affects the print's quality and the object's mechanical properties [60]. Rapid cooling often leads to warping or shrinkage. In contrast, controlled cooling is necessary for materials with higher melting points, such as PEEK, or for composites, and applications that require dimensional accuracy [61,62]. Fans, heated printed chambers, or heated build platforms can help regulate this cooling rate because excessive heat accumulation can cause deformations [63].

Printing parameters, in conjunction with the object's design, play a crucial role in minimizing raw material waste and promoting efficient energy use. Therefore, optimized parameters can facilitate environmentally sustainable manufacturing [64] and efficient energy usage [65]. Materials with high extrusion temperatures, such as Acrylonitrile butadiene styrene (ABS) and PEEK (~230 and ~ 340 °C, respectively), require more energy [66,67] than those with lower extrusion temperatures, such as PCL and PLA, which have melting points of approximately 60 and 190 °C [68,69], respectively. Of course, the material selection also depends on the required properties. Similarly, infill density and layer thickness, which directly impact build quality, are typically achieved at the expense of slow printing, resulting in prolonged energy consumption [70]. These parameters also govern material use, which is essential given that petroleum-based polymers can emit harmful chemicals during printing, with potential environmental and human health consequences [71].

### 2.2. *The industrial potential of FDM*

FDM has been extensively used for years in rapid prototyping to test designs in real-world conditions [72]. Nowadays, the availability of various filaments, ranging from flexible and high-strength materials to biodegradable and conductive options, combined with the widespread adoption of the technology, is also providing manufacturing versatility [73–76]. In medicine, FDM has already been used to create patient-specific implants, prosthetics, anatomical models for surgical planning, tissue scaffolds, and patient-specific medical devices [77–82]. Custom jigs, fixtures, aerodynamic test parts, and lightweight structural components have also been manufactured [79]. Improved strength-to-weight ratios can be achieved using materials such as carbon fiber-reinforced filaments [83]. Plastic parts can be manufactured as needed, thereby eliminating the costs associated with warehousing large inventories, if the performance meets the requirements for replacing injection-molded parts. Components can be produced on demand and customized as needed, thereby reducing storage costs, avoiding overproduction, and providing greater flexibility in meeting demand [79]. Like other AM technologies, it enables localized manufacturing, reducing lead times for shipping parts. A distributed production model can lower logistical costs and increase operational flexibility [25].

FDM 3D printers and related materials are generally more affordable than other AM machines, making them accessible to individuals, small businesses, and large-scale manufacturers [20]. The cost of hardware components has generally decreased over the years, with even more affordable options now available that offer close-to-industrial quality, thereby accelerating product development. Small and medium-sized enterprises (SMEs) can leverage the flexibility and versatility of filament production to experiment with new materials and designs, gaining a competitive edge by rapidly testing and launching new ideas.

### 2.3. *A focus on the flexibility and versatility of FDM*

The FDM’s ability to process a wide range of filaments [55] provides versatility and cross-fertilization of ideas and applications between heterogeneous industrial sectors. FDM filaments can be reinforced with carbon fiber, glass fiber, wood, or metals [84,85]. Biobased and biodegradable (e.g., PLA) or recycled thermoplastics can also be processed into filaments, enabling the fabrication of environmentally friendly components [86]. Biodegradable thermoplastic filaments can potentially reduce environmental impact [87], although evaluating the overall impact of biodegradable plastics remains an open question [88]. Composites can be obtained by integrating them with biodegradable waste such as wood, hemp, or algae [84]. New biocompatible filaments are also continually being developed for the manufacture of affordable medical devices [89–91].

Soft thermoplastic elastomeric materials, such as TPU, can also be 3D printed, offering elasticity and rubber-like properties that are suitable for energy absorption applications [92], scaffolding [93], durability, and stretchability [94], even if there are still multiple challenges to be faced to improve their mechanical properties and interfacial adhesion, among others [37].

Filaments can be manufactured in almost any color for aesthetic purposes and blended with additives to impart specific functionalities, such as glow-in-the-dark effects, conductivity, or antibacterial properties [95]. There is growing interest in “smart” materials, such as shape-memory polymers and color-changing materials that enhance the functionality of printed objects [95]. There is growing support for closed-loop recycling in filament production, where waste prints or post-consumer plastic can be processed into new filaments [86], with promising results, e.g., by compounding recycled PET with low-cost additives [96] or post-consumer recycled Polypropylene (PP) [97].

Multi-material printing capabilities in FDM enable the use of two or more filaments in a single print, offering increased design freedom, even if challenges persist with the adhesion quality at interfaces between dissimilar materials [98,99]. Among future research scenarios in multi-material printing is the exploitation of FDM's versatility with the broad materials palette of Direct Ink Writing (DIW) technology [100]. In the literature, there are also examples of 4D printing solutions supported by FDM [101,102].

A filament can be compatible with various FDM printers, promoting scalability and allowing end-users to choose the material that best suits their machine and application. Filament production can scale to meet varying demand levels, ranging from small batches for hobbyists or custom projects to large-scale production for industrial applications [103]. This versatility has enabled FDM to evolve rapidly, meet diverse demands, and serve as an essential actor in the AM landscape.

### 2.4. *Reflections on some 3D-printable thermoplastic polymers and their sustainability potential*

Synthetic polymers are considered bioplastics under these conditions (or a combination of them) [104]: they have been derived/extracted from biomass compounds (i.e., they are bio-based); they are biodegradable; they are obtained through biological processes. PLA is a bioplastic because its monomers are derived from renewable vegetable sources [105], but the polymerization process is chemical [104]. Polyhydroxyalkanoate (PHA) is also a bioplastic, but unlike PLA, it is biologically synthesized and degrades more quickly [104]. PVA and PCL are biodegradable, but they are fossil-based [104,106,107] and therefore preferably not included in the bioplastics category [104].

Biodegradability is a characteristic common to all four thermoplastics – PLA, PHA, PCL, and PVA – which have promoted their use in various applications [108]. With respect to these materials, studies related to FDM have focused on preserving or improving their degradability and on enhancing their mechanical properties (especially for bio-based plastics in general, this is a critical target [109]), processability, and functionalization. A brief overview of these polymers’ characteristics, based on general and FDM-based studies, is provided in the following subsections. Further works in the field of MEX involving these materials will also be provided in later Sections of this study.

#### 2.4.1. *Polylactic Acid (PLA)*

With sufficient strength and biocompatibility, PLA exhibits characteristics like those of common polymers, offering good mechanical processing performance and low shrinkage [110]. However, efforts are underway to identify PLA-based blends that improve its mechanical and thermal properties, for example, by incorporating crystalline nanocellulose [111] or mixing it with PHA [112] to preserve biodegradability. PLA can be recycled and used as a polymer matrix to accommodate additives from biomass, making it a viable choice for producing value-added entities [47,113]. Having also been approved by the Food and Drug Administration (FDA), multiple biomedical applications have been explored [114]. However, because it degrades slowly, its complete degradation within current landfills and industrial composting infrastructure has significant environmental impacts [115]. Efforts are underway to address these issues and accelerate this process [116]. Also, since the recycling process can degrade mechanical properties [117], investigating degradation rates and using sustainable additives and recycling parameters that preserve mechanical properties is key.

#### 2.4.2. Polyhydroxyalkanoates (PHAs)

PHAs are promising biodegradable materials with potential use in multiple fields, including medicine and agriculture [118]. Their biocompatibility makes them relevant for tissue engineering and regenerative medicine [119,120]. Besides, it has been demonstrated that it can be degraded by microorganisms even in challenging settings, such as the deep-sea floor [121].

However, their use is limited by their significant production costs [122]. Besides, their potential in AM remains limited due to their low mechanical strength and the need to optimize the printing process [123], even though attempts have been made to reinforce them, again exploiting cellulose nanocrystals as fillers [124]. Therefore, challenges such as low mechanical strength, warping issues, and the feasibility of using it as a matrix for sustainable additives must be addressed to promote their adoption.

#### 2.4.3. Polycaprolactone (PCL)

PCL has a glass transition temperature (Tg) of approximately − 60 °C [68], making it suitable for applications requiring mechanical compliance with biological tissues [125]. This low Tg ensures flexibility at body temperature, making it an interesting material for designing wearable, adaptable, and biodegradable solutions. Additionally, this feature is crucial for 3D-printed drug delivery devices, as it maintains stability during the processing of medicines within the manufactured carrier [126]. Since it melts at about 60 °C [68], the risk of heat degradation of biomolecules or drugs incorporated into the polymer matrix is reduced. When it biodegrades, it produces breakdown products that the body can gradually metabolize [127]. Furthermore, good mechanical properties, such as high elongation at break and good-enough tensile strength, are also observed in 3D-printed PCL samples. These characteristics can also be tuned by adjusting the molecular weight of PCL to achieve specific properties or by combining it with other polymers [128]. New biodegradable blends can be created by mixing PCL, for example, with PLA and Polyhydroxybutyrate (PHB) [129,130], or by introducing functional particles (e.g., Fe3O4) and reinforcements (e.g., cellulose nanofibers) to functionalize it and increase its mechanical strength [131].

Its biodegradability and non-toxicity make it an interesting polymer, whose relevance is expected to grow in the future [132]. However, further studies on the influence of the recycling process on its properties, biodegradability strategies, and behavior in combination with bio-additives are needed to strengthen its role as a sustainable material for MEX.

#### 2.4.4. Polyvinyl alcohol (PVA)

PVA has a relatively low melting temperature and exhibits a range of interesting properties, including water solubility, biodegradability, adhesive capacity, and biocompatibility. Attempts to enhance its mechanical properties, thermal processability, and electrical conductivity have been made by blending it with carbon nanotubes [133], graphene nanocomposites [134], cellulose nanocrystals [135], and ionic liquids [136]. There are also several attempts in the biomedical field, such as blending PVA and PCL with chitosan to produce antimicrobial filaments with potential applications in tissue engineering and regenerative medicine [137]. Further attempts have also been made to develop PVA-based blends for patient-specific drug delivery systems [138–141]. Its intrinsic and hygroscopic nature limits its potential applications, but studies are ongoing to tackle this issue [142]. Despite its role as a drug carrier and its biocompatibility and biodegradability, the scarcity of investigations into value-adding agents, for example, derived from waste, and their recyclability for MEX, remains a limiting factor for the adoption of PVA as a potentially relevant sustainable alternative.

### 2.5. Driving trends in filament fabrication technology

In recent years, we have seen increased interest and significant advancements in filament extruder technology, which have boosted the flexibility previously discussed in FDM. This technology can transform the landscape of 3D printing by making the study and development of filaments with enhanced properties and novel composites more affordable. Its significant rise has also spurred researchers to explore novel filament compositions to achieve environmentally sustainable objectives [143]. In some cases, as discussed later, new filaments are created to convert waste from other streams into new 3D-printable materials or to convert 3D-printed scraps into new 3D-printable materials.

Filament extruders are machines/systems that transform raw thermoplastic or composite materials into filament spools [144]. Industrial-grade extruders have become increasingly sophisticated to support mass-scale production; they often lack customization, as the physical composition of the filament spool is predetermined by the parameters and raw materials selected during the manufacturer's compounding process [145]. To address this lack, desktop-based, versatile lab-scale filament extrusion systems have emerged on the market [146]. Examples of manufacturers of commercial desktop filament extruders are Filabot (https://www.filabot.com), Felfil (https://www.felfil.com), Noztek (https://www.noztek.com), 3devo (https://www.3devo.com), and FilaFab (https://www.filafab.co.uk). Fig. 2 shows the various components involved in the filament fabrication.

The key component of these machines is a motor-driven, endlessly rotating single- or multi-stage screw that conveys, melts (in combination with heating coils), and homogenizes the raw material (typically thermoplastic pellets/scraps/granules from a previous shredding process) [144]. The material is pushed towards a die or nozzle (Fig. 2**a,b**) to extrude filaments of sizes 1.75 and 2.85 mm, based on the selected nozzle. The extruded material is then passed through a cooling system (e.g., air and water in some cases) before being wound into spools through a dedicated system [147], such as the spooler in Fig. 2. The parameters that govern filament extrusion include extrusion temperature, cooling rate, screw rotation speed, and the desired filament diameter (Fig. 3).

It is worth noting that how the molten polymer flows through the die is crucial for achieving high-quality filament; the extrusion temperature influences this flow. However, increasing the temperature beyond the required level can lead to overextrusion, while decreasing it can cause clogging. Likewise, unoptimized auger screw rpm can also imply over-extrusion at higher rpm or under-extrusion at lower rpm, compared to what is required to push the thermoplastic polymer through the nozzle. Similarly, the cooling rate is vital for solidifying the molten plastic and achieving the desired filament diameter.

Thanks to advances in extruder technology, the variety of filaments available has been further expanded to include specialized composite filaments, some of which are still at lab-scale, exhibiting increased strength, flexibility, heat resistance, or eco-friendliness. An overview, not intended to be exhaustive, of available studies is provided in Table 1.

This brief overview shows how this high versatility in raw material production has enabled researchers and manufacturers to design more functional and performing, particularly composite filaments, with a wide range of thermoplastic materials explored, including bio-based composites. This point will also be discussed later. In such a context, studies such as [181] are also fundamental because they provide eco-informed design guidance on exploiting reinforcement fibers in polymers with potential applications in FDM.

Therefore, research in this field must proceed with the aim not only of producing new “green” filaments from eco-friendly, recyclable materials or strategies for repurposing waste, but also of supporting faster, more efficient methods to optimize material manufacturing parameters and to exploit these new materials in potential applications. Indeed, the consistency of the available filament diameter plays a crucial role in influencing printing quality [182] and the feasibility of setting up

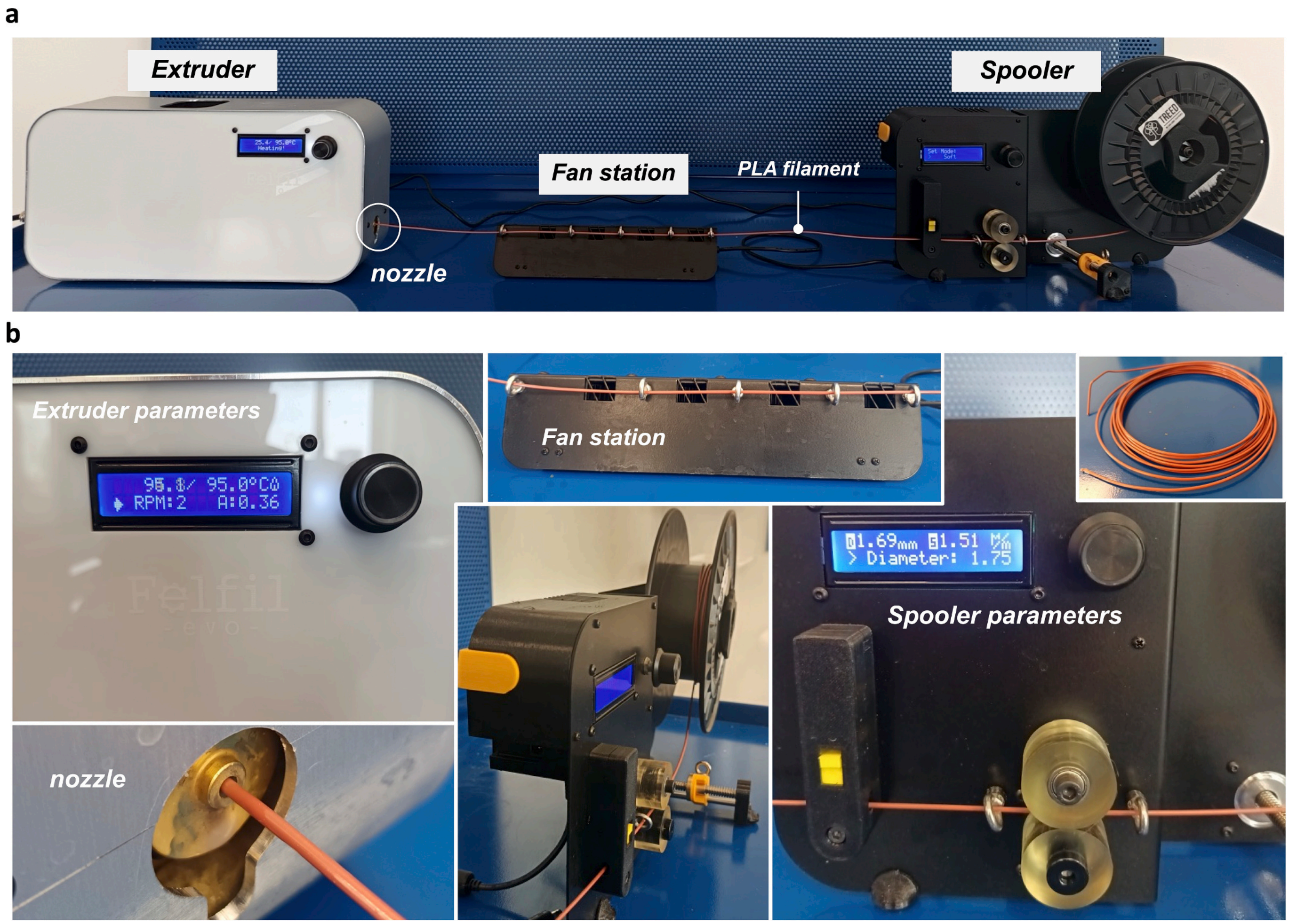

**Fig. 2.** An example of desktop-based filament extrusion technology by Felfil (www.felfil.com). **a)** The default configuration, from left to right, includes an extruder with its nozzle, a cooling station to solidify the extruded filament, and a spooler that checks the filament diameter and creates the spool. **b)** Some details of the extrusion technology presented in **(a)**: main extruder parameters, the nozzle, the fan station, and the spooling system with its main parameters visible on a screen. The outcome, i.e., the filament, is also shown.

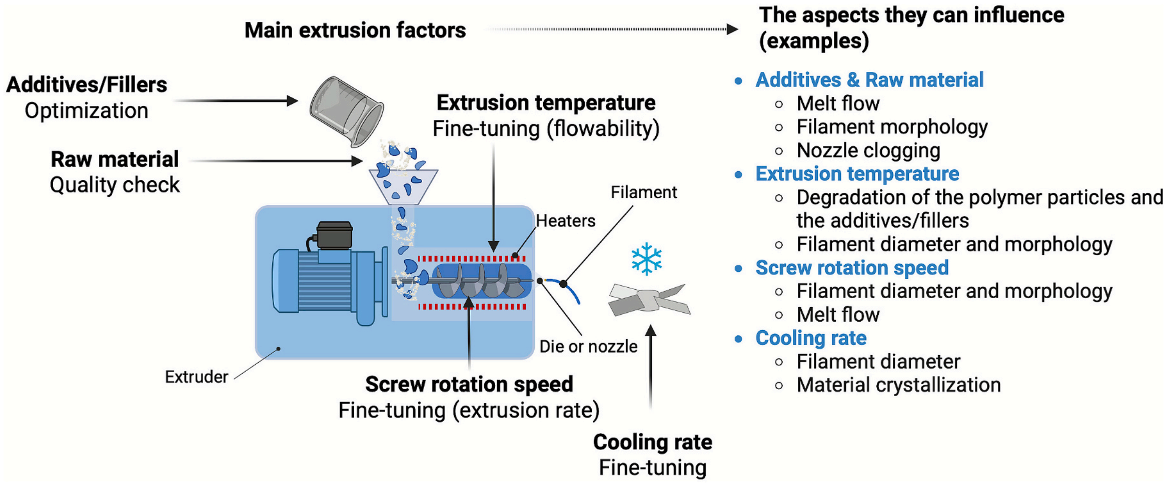

**Fig. 3.** Overview of the key aspects and potential issues related to the extrusion stage of the filament manufacturing process. The winding stage and related parameters are not represented. The extrusion stage is shown in simplified form and is not meant to be exhaustive of all aspects to be considered or of their potential mutual influence. For details and precise explanations, see the study [148], whose results have inspired this image and have been generalized and reinterpreted with respect to the content of the present study. Created in BioRender. Graziosi, S. (2026) https://BioRender.com/jzcw3ae.

**Table 1**
Overview of some examples of desktop-based filament extruders employed to create new 3D-printable filaments. The created material, its potential applications, and the material manufacturing details (where available) are also provided. The related reference is also specified. This list is not complete, nor is the number of examples for each manufacturer representative of the distribution of that specific machine. The data provided are representative. Readers are invited to consult the relevant reference for all details, as typos may be present.

| Machine Manufacturer | Material | Application or study's aim | Extrusion Temperature [°C] | [rpm] of the screw | Filament diameter (obtained or planned) [mm] | Ref. |
|---|---|---|---|---|---|---|
| **Felfil** | PLA/Rice husk | Structural applications | 177,187,197 | 5–8 | 1.75 | [149] |
| | PLA/Insoluble keratin | Waste poultry feathers reuse | 187 | 6 | 1.75 | [150] |
| | Recycled PLA | Waste management of PLA | 170 | 5–7 | 1.68 ± 0.07 | [117] |
| | Poly(butylene adipate-*co*-terephthalate) (PBAT)/ Zein-titanium dioxide (TiO2) complex microparticles | Biomedical scaffold applications | 150 ± 10 | 3 | 1.65 ± 0.10 | [151] |
| | PLA/niclosamide and graphene nanoplatelet | To develop a novel drug delivery device | 190–200 | 4–8 | 1.75 ± 0.05 | [152] |
| | PCL/$\beta$ −Tricalcium Phosphate | 3D printing of personalised scaffolds with improved mechanical and biological properties | 95 | 2 | 2.85 | [153] |
| | PLA − PCL / Fe3O4 nanoparticles | Novel, low-cost magnetically active composite material | ~ 90 − ~ 150 | – | 1.75 | [154] |
| | PLA/Carbon nanofiber | Upcycle 3D printing filament scraps for manufacturing rechargeable Zn-I$_2$ batteries | 175 | 8–9 | 1.75 | [155] |
| **3devo** | PEEK/Amorphous magnesium phosphate | Bioactive composite for implant development | 380–360 | 15 – 6/8 | 1.75 ± 0.10 | [148] |
| | PLA/cocoa bean shell waste | Cocoa bean shell reuse | 165–200 | 4 | – | [156] |
| | PLA/Lignin | Enhanced mechanical properties | 230 | 3.5 | 1.75 | [157] |
| | Recycled PLA and recycled PLA/ceramic waste | To demonstrate the feasibility of recycling artisanal waste | 190–220 | 3.5–4 | 1.75 | [158] |
| | PLA/Cellulose nanofibrils | Enhanced cellulose dispersion in filament matrix | 165–175 | – | ~1.75 | [159] |
| | PCL/Hydroxyapatite (HA) | Novel material for scaffolds 3D printing | 66 | 5 | 1.75 ± 0.05 | [160] |
| | Polypropylene (PP)/High and low concentration of inorganic additives | To develop a novel filament from PP waste recovered from electric and electronic apparatus (WEEE) | 178–186<br>190–205 | 2.5–5 | ~1.75 | [161] |
| | PET | Recycling PET bottles for generating PET filaments | 265 | 3.6 | 1.75 ± 0.05 | [162] |
| | High-density polyethylene (HDPE)/ Antimony Tin Oxide (ATO) | Influence of the nanocomposite in improving mechanical response | 200–210 | 7 | 1.65–1.85 | [163] |
| **Noztek** | PLA/Agave tequilana bagasse fibres | Agriculture byproduct reuse | 175–185 | – | 1.75 | [164] |
| | Recycled ABS/Virgin ABS | Reuse of recycled filament to reduce material cost | 180, 190, 200 | 40 | 1.65 ± 0.1 | [165] |
| | PLA/Nona and Soy fibres | Novel method to 3D print composites | 195 | 15–20 | 1.75 ± 0.21 | [166] |
| | ABS/Aluminium and stainless steel alloy particles | To develop of novel metal-based filaments | 150 | – | 1.75 | [167] |
| | Zirconia-based filament | Manufacturing of cost-effective ceramic based implants | 85–125 | – | 2.85 | [168] |
| | Polyetherimide (PEI)/recycled carbon fibers (rCFs), thermal black (TB) particles and their combination | Novel material to be used in the field of mobility (aircraft interiors and ground transportation applications) | 370–390 | 25 | 1.75 ± 0.05 | [169] |
| | Waste PP/Short basalt fibres | Exploit the basal fibres to reinforce the recycled PP | 220–225 | 12 | 1.35–1.55 | [170] |
| **Filabot** | E-Waste, mainly Polycarbonate (PC) | E-Waste recycling | 205 | 40 | 1.72 ± 0.3 | [171] |
| | PC/Silica | Thin film interfaces for optical transmittance | 260–265 | – | 1.5 ± 0.1 | [172] |
| | PCL/Sodium Alginate (SA) | A novel composite filament to 3D print structures capable to adsorb heavy metal ions | 90 | – | 1.75 | [173] |
| | PP/40 wt% carbon black | A novel electrically conductive filament for applications in the field of electrochemistry | 210 | – | 1.75 | [174] |
| | PP/Paraffin wax | To 3D print porous separators to be used for 3D printed battery architectures | 160 | – | ~1.75 | [175] |
| | PLA/Hydroxyapatite (HA) | To develop a novel material for the field of tissue engineering (e.g., patient-specific scaffolds) | 175 | – | 1.5–1.75 | [176] |
| **FilaFab** | Recycled Polyvinyl butyral (PVB) | Waste management of PVB | 155 | – | 1.75 ± 0.25 | [177] |
| | PLA/Recycled fiberglass, from end-of-life wind turbine blades | Novel composite filament exploiting the use of recycled fiberglass recovered from end-of-life wind turbine blades | – | – | 1.75 | [178] |
| | Polyethylene (PE)/Martian regolith | Novel materials for future space explorations (Moon and Mars) | 122–125 | 5 | 2.90 ± 0.02, 2.89 ± 0.01 | [179] |
| | PLA/carbon dot nanocomposites | To improve mechanical properties | 130 | 15 | 1.70–1.85 | [180] |

industrial-scale production. Processing parameters such as extrusion temperature, cooling time, and extruder nozzle diameter are critical to determining this aspect [183]. In addition, studies that offer a lifecycle perspective on the collection, management, and use of the raw materials required to produce these promising new filaments are needed. They are fundamental to demonstrating robustness, environmental impact, and their potential scalability into industry.

### *2.6. Plastic upcycling into new products: The role of FGF and FDM and open issues*

In this Section, we review examples of available solutions and studies with potential upcycling applications involving creating new products (Fig. 4). As a first example, one can mention the *Print your city project* [184], where 3D-printed street furniture has been created from plastic waste using robotic 3D printing (pellet-based). Similar technology has also been used to 3D-print furniture from discarded ocean plastic in the *Ocean Plastic Project* [185]. The company *vanPlestik* [186], with its own large-scale 3D printers, produces products such as chairs, tables, and lamps made from recycled plastic. *Aectual* is another company working in the field of circular furniture and finishes platforms, exploiting large-scale 3D printers [187]. A robotic arm equipped with an extruder has been used to 3D-print a four-meter-diameter suspended chandelier from recycled PET pellets [188]. LG Project Management and Caracol AM collaborated to 3D-print the first mobile living module, starting with a recycled PET-based polymer reinforced with glass fiber [189]. Byard et al. [190] utilized shredded recycled ABS and PP as feedstock for FGF to produce skateboards, kayak paddles, and snowshoes. In [191], plastic waste was used to produce fiber-reinforced concrete, which was 3D-printed using a paste-based extrusion system. Using FGF printers, recycled polyolefin-based composites can also be obtained by combining the matrix with various natural fillers, such as cellulose or sawdust, as reviewed in [192]. In [193], FGF has supported multi-material recycling of PET and HDPE, and the feasibility of this approach has also been demonstrated by printing a children's chair. However, further research efforts are needed to optimize the blend.

There are also examples exploiting filament-based extrusion processes. Novel filaments have been created in [194] by blending recyled HDPE and PP, and by mixing this blend with biocarbon; these filaments have been succesfully used to 3D print a spectacle frame and elliptical gears with a shaft. Plastic Thinkers [195] uses PET waste to produce 3D-printable filaments and various products. Interestingly, STL files are available online showing what can be created as daily products from recycled 3D-printed parts [196]. A study on the closed-loop additive manufacturing of ABS was conducted by Kim et al. [197], which demonstrated the potential of FDM to upcycle ABS into re-printable, mechanically robust ABS vitrimers.

Therefore, ideas are available. Although further efforts are needed, for example, to guarantee that the overall process is sustainable, from an environmental and economic point of view. Besides, technical difficulties in 3D printing plastic waste, such as poor bed adhesion, weak interlayer bonding, and deformities caused by contaminants, can challenge the printing process [198] and must be addressed effectively and systematically. Deterioration of mechanical properties can occur, especially in FDM and to a lesser extent in FGF (as demonstrated in [199] for PLA), in combination with new process parameters or processability issues [200–202]. Promising mechanical property results have been obtained with FGF using recycled carbon fiber/ABS composite granules [33]. However, this study also underscores that, if the material is recycled in a third life and beyond, alternative recycling strategies should be considered to address potential declines in mechanical properties [33]. The deterioration of microstructure and mechanical properties after multiple recycling cycles has also been observed in flax fiber-reinforced PP composite granules [203]. Therefore, strategies are needed to address this issue [203]. More efforts invested in material traceability [204] could also help towards this target. Besides, in such a context, costs also play a key role; indeed, the price of the recycled polymer relative to virgin polymer and the cost of the recycling process relative to alternative disposal procedures are the two key economic drivers that influence the viability of recycling thermoplastics [205].

Thus, innovative and synergistic approaches spanning technical, logistics, and marketing aspects must be implemented to tackle these

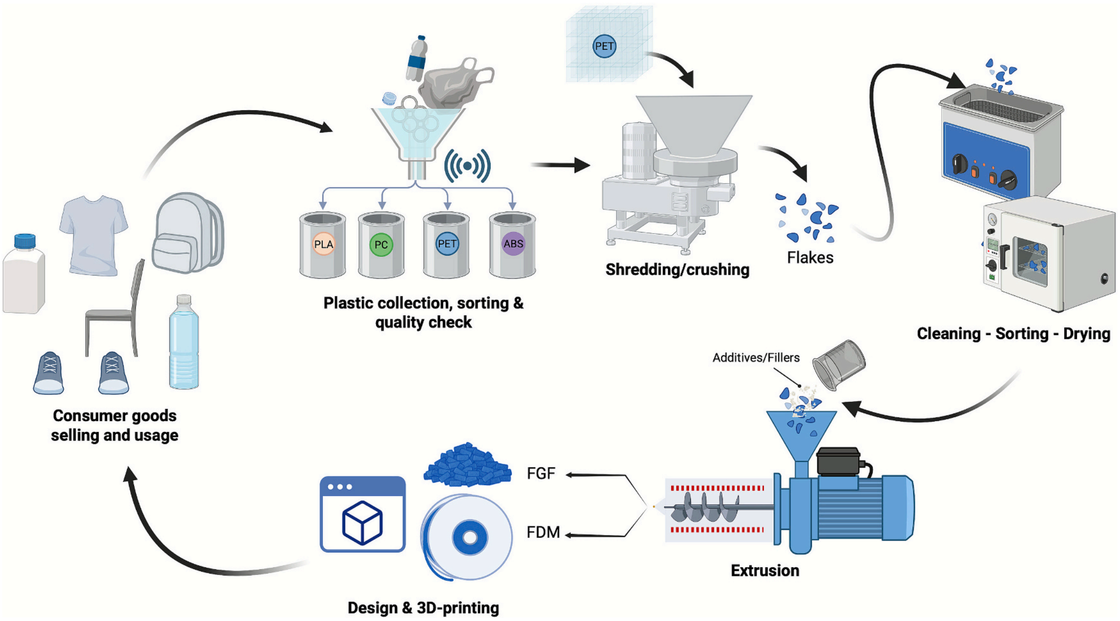

**Fig. 4.** Simplified illustration showing the potential upcycling process of thermoplastic materials using FDM and FGF 3D-printing. This illustration is not intended to be exhaustive in its representation of the various stages of the mechanical recycling process. Besides, for illustration purposes, the image refers to post-consumer sources. Post-industrial sources should also be included, bearing in mind that there are relevant differences in values and handling routes between these two waste streams [4]. Once the plastic is shredded, cleaned, and dried, it can be processed and blended with additives (if needed) to create new materials in the form of filaments or pellets, which can be used to develop new products. The phases required to make the filaments are not shown in this figure. Figure inspired by [51]. Created in BioRender. Graziosi, S. (2026) https://BioRender.com/zqcrbr5.

challenges and effectively promote MEX as a potential further manufacturing asset for sustainable upcycling of thermoplastic waste.

## 3. Biomass upcycling: From waste to value-added products

### 3.1. Examples of MEX materials using biomass waste as fillers

Biomass derived from agri-food processing can be used directly to functionalize materials, e.g., to provide flame-retardant properties, among others, as demonstrated with waste coffee grounds [206]. Attempts of this kind have also already been explored with MEX. An overview of some studies is provided in Table 2.

As shown in Table 2, although the provided list is not intended to be complete, a significant number of contributions are available for FDM, and this number is rapidly growing, as is the case for FGF. The biomass filler is often used as reinforcement, while other studies show that its addition allows a reduction in the percentage of thermoplastic matrix without significantly reducing material performance. It is also important to underline that when creating these new blends, it is crucial to ensure appropriate adhesion between the matrix and the natural filler to enable load transfer and, consequently, a composite with enhanced mechanical properties [192]. Therefore, multiple research paths must be pursued, and further studies are expected.

### 3.2. Biomass waste as bioactive compounds for health-promoting applications

Biomass can also be transformed into sources of bioactive natural compounds that can interact with elements in living tissues to exert beneficial effects [227,228]. These compounds can influence various physiological processes and are known for their potential health benefits, including polyphenols, proteins, lipids, and numerous other bioactive components with multiple applications [229–232]. In particular, the use of biomass-derived bioactive compounds is increasingly prominent across the food, pharmaceutical, cosmetic, and healthcare industries (Fig. 5).

In the cosmetic sector, fruit and vegetable by-products, such as pomace and peels, are increasingly used as sources of bioactive molecules with health-promoting effects. For example, pectin recovered from tomatoes and citrus is an effective anti-inflammatory compound with applications in the biomedical sector [233]. Furthermore, it can also be used in the food industry for its thickening, gelling, and emulsifying properties [234]. Similarly, limonene, a primary compound in citrus essential oil and a major component of citrus peel waste, plays a significant role in the flavor and fragrance market, with applications across the cosmetic, nutraceutical, and pharmaceutical sectors [235]. Furthermore, vegetable oils derived from nut seed or fruit waste, such as avocado or olive, can be extracted and valorized by the cosmetic industry due to their benefits for both skin and hair [236–238].

Food waste resulting from the processing of plants and animals can also provide excellent ingredients for both food supplements intended for human consumption and animal feed [239,240]. Bioactive peptides, short chains of amino acids derived from protein hydrolysis, are emerging as promising multifunctional ingredients for disease prevention. These peptides, which are derived from plant seed wastes (e.g., soy, sunflower, hemp, or olive seeds), represent an excellent source and can be effective in managing blood pressure, regulating cholesterol levels, improving immune system function, and exerting numerous other health-promoting effects [241–247].

In addition to plant-based biomass, animal by-products such as fish, poultry, and dairy waste can also be used to extract bioactive peptides (Fig. 5). These peptides often exhibit potent antioxidant, antimicrobial, and antidiabetic properties, making them valuable for human health, veterinary medicine, and animal feed in agriculture [248–250]. Furthermore, peptides extracted from algae by-products or from meat or fish processing waste, such as collagen peptides, are increasingly being

**Table 2**
Overview of some studies focused on the MEX technology to valorize biomass for enhancing properties and functionalizing thermoplastic matrices. This overview is not intended to be exhaustive of all available studies; besides, it is limited to the FDM and FGF technologies. Readers should refer to the references for further, more precise details about the specific study.

| Matrix | Biomass | Study objective | MEX technology | Ref. |
|---|---|---|---|---|
| PP | Cocoa bean shells | Composite with improved tensile strength and fracture strain | **FDM** | [207] |
| PP | Hemp fibers | Composite with increased tensile strength and Young's modulus. | **FDM** | [208] |
| Polyethylene terephthalate glycol (PETG) | Activated carbon from waste leaves | 30% enhancement in mechanical properties compared to neat PETG (anatomical models and filter mesh where 3D-printed) | **FDM** | [209] |
| PLA | Lignin nanospheres | Increased mechanical properties (flexural strength, tensile strength and impact strength) | **FDM** | [210] |
| PLA | Hazelnut powder | Repurposing hazelnut shell agricultural waste for creating a novel bio-composite material to be used for product design | **FDM** | [211] |
| PLA | Walnut shells, eggshells, and white marble particles | Increment in the melting point and improvement of flexural properties | **FDM** | [212] |
| PLA | Crab shell powder from waste | 3D-printed bone scaffold with increased tensile and flexural strength | **FDM** | [213] |
| PLA | Wood fibers | Enhance the flexural properties | **FDM** | [214] |
| PLA | Pistachio shell | Promising applications in food packaging | **FDM** | [215] |
| PLA | Potato starch | 3D printing of personalized anatomical models and scaffolds | **FDM** | [216] |
| PLA | Sea urchin residues | Reinforced biocomposite with potential applications in biomedical, construction and packaging fields | **FDM** | [217] |
| PCL | Wood | Increased tensile properties | **FDM** | [218] |
| PCL | Cocoa shell waste powder | A novel biofilament with household and biomedical potential applications | **FDM** | [219] |
| PCL | Chitin nanocrystals | A novel biocompatible and biodegradable composite for applications in the biomedical field | **FDM** | [220] |
| PCL | Waste wool particles | A novel composite filament with various potential applications (e.g., | **FDM** | [221] |

(continued on next page)

**Table 2** (*continued*)

| Matrix | Biomass | Study objective | MEX technology | Ref. |
|---|---|---|---|---|
| | | toys, packaging, industrial tools) | | |
| PHB-PLA | Corncob wastes | Explore the potentialities of using corncob waste for the manufacturing of a novel environmentally friendly polymeric composite. | **FDM** | [222] |
| ASA (Acrylonitrile styrene acrylate) | Cork waste | A not significance decrease of mechanical properties is obtained therefore promoting a reduction of the ASA content in the composite. | **FGF** | [36] |
| PLA, recycled LDPE, HDPE | Spent Coffee Grounds | Valorize biomass scraps/by-products and new product applications | **FGF** | [223] |
| PLA | Wood fibers | Development of a design framework for promoting the use/ development of novel materials for FGF | **FGF** | [224] |
| PLA | Pine wood | 3D-printed bat houses | **FGF** | [225] |
| PETG | Olive pits | Valorisation of the agro waste exploiting surface-modification strategies to promote compatibility between the matrix and the waste | **FGF** | [226] |

used in the cosmetic sector. These peptides exhibit moisturizing, wound-healing, and anti-aging properties, making them a popular ingredient in skincare and hair-care products [251–253]. Moreover, these peptides exhibit a range of functional properties, including solubility, water retention, oil binding, foaming, and emulsifying, demonstrating significant potential for various industrial applications. In fact, in the food industry, they can be used as emulsifiers, foaming agents, and texturizers; in the cosmetic industry, they serve as effective moisturizers and hydrators [254].

To obtain active molecules from biomass, different methodologies and techniques are applied. Traditional extraction procedures for bioactive molecules, such as Soxhlet extraction, distillation, and maceration, often involve hazardous solvents, substantial energy consumption, and lengthy processing times, rendering them inefficient and environmentally detrimental [255,256]. To address these issues, green extraction techniques have evolved as more sustainable options. These processes are energy-efficient, utilize ecologically friendly solvents, and yield higher-quality products. Green extraction methods include fermentation, which uses microorganisms to break down biomass into bioactive compounds; enzymatic hydrolysis, which uses enzymes to release bioactive peptides from plant material; microwave heating, which speeds up the extraction process; and supercritical fluid extraction, which uses supercritical carbon dioxide to extract compounds without the use of toxic solvents [257,258]. Additionally, the use of green solvents, such as ionic liquids, deep eutectic solvents, and water, can further reduce the environmental impact [259].

The combination of these green extraction techniques enables more sustainable and cost-effective methods for obtaining valuable bioactives, thereby increasing the efficiency of biomass valorization and supporting the transition to a circular bioeconomy. With the growing demand for natural, functional, and sustainable products across agriculture, food, pharmaceuticals, and cosmetics, biomass valorization will continue to play a key role in shaping a greener, more sustainable future. This scenario represents an excellent opportunity to utilize biomass and valorize by-products [201] as feedstocks for MEX, thereby developing bio-friendly products that could contribute to environmental sustainability [51]. However, high processing temperatures could compromise the thermal stability of biomass when used as an additive [260]. If these issues are addressed, new options exist to valorise biomass through MEX, promoting greener 3D-printable solutions that can achieve scaled production.

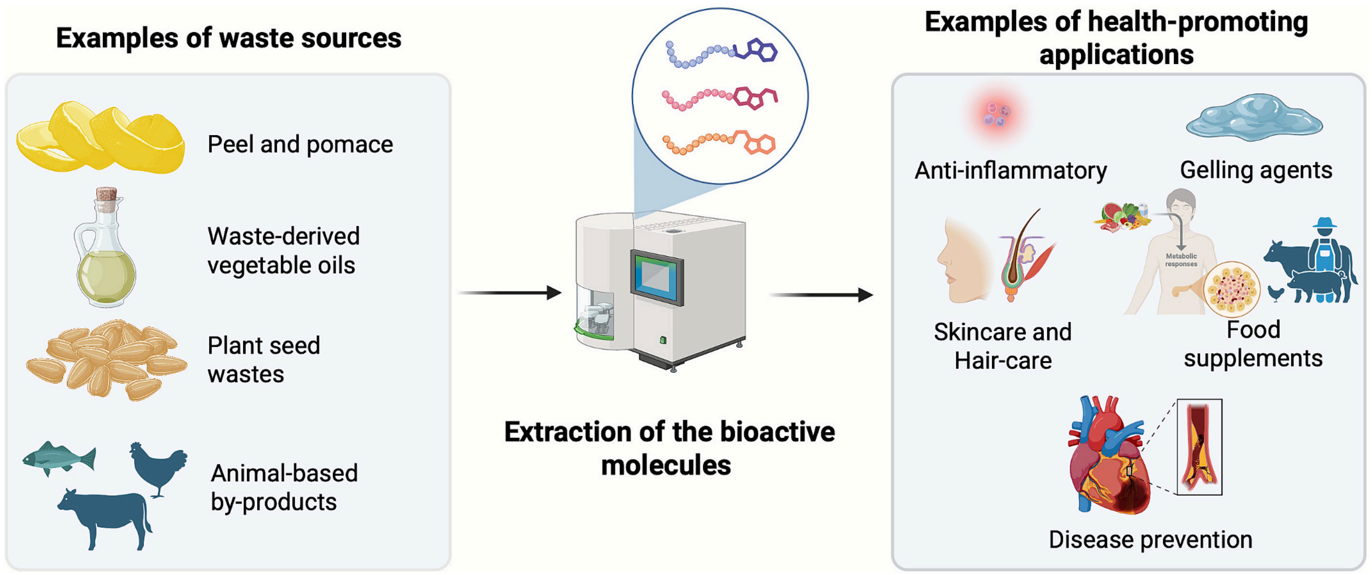

**Fig. 5.** Schematic representing the concept of biomass waste valorization. On the left are examples of waste sources. On the right, examples of health-promoting applications where this waste can be upcycled once bioactive molecules are extracted. These examples are related to the cosmetic, healthcare, food, pharmaceutical, and animal feed industries. Created in BioRender. Graziosi, S. (2026) https://BioRender.com/vx1gqe3.

### 3.3. Exploiting bioactive compounds from biomass waste into 3D printable MEX-based materials

A bioactive material can be either natural or synthetic, exhibiting biocompatibility and inducing therapeutic activity in biological entities [261,262]. Regardless of their sources, the aim is to achieve bioactivity [263] and to interact with biological systems. Synthetic methods use fresh precursors, solvents, and artificially synthesized reagents, which can lead to higher costs and greater chemical waste. In contrast, bioactive compounds from natural sources are typically derived from biowastes, offering opportunities for green synthetic methodologies [264,265]. Bioactive materials are usually made from biocompatible polymers that can be used with living tissues [266,267]. They can be infused with bioactive agents, such as antimicrobial particles, growth factors, or drug-delivery compounds, to enhance their functionality in medical, dental, or tissue-engineering applications [120,268].

If these materials were conceived to 1) reach their purpose by using recycled content as the primary matrix, 2) use waste material from other sources as the bioactive content, and 3) be biodegradable (even inside the human body), they could represent a potential strategy to provide benefits not only to humans but also to the environment. Medical waste is among the nine major types of waste affecting countries and their urban systems [269]; achieving sustainability in surgical practices is key [270]. This strategy alone would be insufficient to produce a significant impact. However, it represents a further possible approach to promoting more environmentally conscious practices and upcycling solutions.

Biomass-based bioactive compounds are non-toxic and degrade more quickly, making them a promising strategy for achieving sustainable environmental targets [271,272]. Anti-oxidative, antibacterial, and anticarcinogenic properties are a few of the many that can be derived from biomass and could be successfully transferred into 3D-printable materials using existing technologies, thereby developing value-added, sustainable products [273,274].

#### 3.3.1. An introduction to bioactive filaments

Bioactive filaments are crucial in biomedical engineering and personalized medicine, enabling the creation of customized medical devices, implants, and prosthetics with active biological functions [77,275]. 3D-printed structures can guide tissue regeneration, such as skin, bone, or cartilage, by promoting cell attachment and proliferation. Additionally, 3D-printed implants or patches can slowly release drugs, providing localized treatment for conditions like infections, burns, or cancer [276,277]. Bioactive filaments derived from biodegradable polymers, such as PLA or PCL, are crucial for temporary medical devices or tissue scaffolds. These materials naturally degrade in the body over time, eliminating the need for surgical removal. During degradation, they can support tissue regrowth or drug release, thus allowing the integration of the newly formed tissue [278,279]. Bioactive filaments enable the development of customized medical solutions tailored to an individual’s anatomy or medical condition, which are particularly valuable for custom implants used in bone repair, patient-specific drug delivery systems that optimize dosage and treatment effectiveness, and prosthetics or assistive devices that can be adjusted to fit the end-user’s anthropometric characteristics [280].

In such a context, bioactive compounds from natural materials could emerge as a more sustainable alternative in biomedical applications. For example, animal-based fillers safely degrade after usage by breaking down into harmless substances for health [281]. Besides, these bio-additives occupy a portion (even if small) of the polymer matrix, reducing the overall amount of plastic used in material manufacturing. In terms of studies, e.g., Rosales et al. [282] reported impregnating ethanolic extracts of mango leaves into PLA filaments for FDM and observed enhanced anti-denaturation and antioxidant properties [282]. Ahmed et al. [283] designed and studied 3D-printed medical threads [283] using seed waste husks from pistachio, coffee, chestnuts, and walnuts in a PLA matrix. The study indicates that the additives successfully induce anti-bacterial properties and improve mechanical properties. Robles et al. [273] incorporated lignin into PLA to produce an FDM filament with antioxidant properties. They observed the filament's ability to scavenge reactive oxygen species.

All these reflections underscore that the use of bio-based bioactive compounds can enable interesting healthcare applications for MEX. Their integration into medical practices could enhance patient outcomes, reduce healthcare costs, and minimize the environmental impact of medical materials.

#### 3.3.2. Technical challenges on the 3D printing of bioactive filaments

Developing bioactive filaments requires considering several essential aspects to preserve the mechanical and biological functions of printed parts [284–286]. Filaments typically used in medical, tissue engineering, and pharmaceutical applications must be handled carefully during the MEX process to maintain their bioactivity, biocompatibility, and structural integrity [266,267,287]. Indeed, the extrusion process and printing parameters (Fig. 6) must be carefully selected to prevent premature release or deactivation of the bioactive agents during printing [288]. For bioactive applications, especially in tissue engineering, the biodegradation rate of the printed structure is critical; hence, the extrusion process can influence the material’s porosity and internal structure, which in turn affects how quickly it breaks down in the body; also, by controlling parameters like infill density and layer height, the biodegradation rate can be regulated [289].

Because of this, emphasis is placed on the material composition. Biocompatible thermoplastics such as PLA or PCL are preferred for their biodegradability and bioinertness, as they tend to break down safely yet slowly in the environment [87,290]. Additive integration, such as antimicrobials, growth factors like bone morphogenetic protein-2 (BMP-2), ceramic particles (e.g., hydroxyapatite for bone growth), or drug molecules, plays a vital role in the bioactive ability of filaments; bioactive filaments are therefore composite materials, combining polymers with bioactive ceramics or different types of nanoparticles [78,291–294]. The extrusion process must account for the properties of the polymer and the additives, which can affect melt flow and cause nozzle clogging [295].

Many bioactive agents (e.g., proteins, peptides, drugs, or antimicrobial compounds) extracted from biomass can be sensitive to high temperatures. In FDM, the filament is typically melted at temperatures between 90 °C and 250 °C, depending on the material used. Therefore, optimized control of the extrusion (nozzle) temperature is needed to avoid degradation of the bioactive agents [296,297].

Thermoplastics with melting temperatures compatible with those of the additives are typically selected to preserve the bioactive compounds' functionalities. Thanks to their relatively low melting points, polymers such as PCL are potential candidates to produce bioactive filaments [278,279]. The nozzle temperature can also affect the tensile strength and elastic modulus of bioactive filaments [266]. Additionally, nozzle diameter and layer thickness are crucial for achieving high printing resolution. Finer nozzle diameters (0.2 mm) can improve surface quality but may lead to clogging [156]. Moreover, optimizing the flow rate and print speed ensures effective printing, as improper flow rates can lead to irregular distribution of bioactive components and reduced mechanical properties. Bed temperature, in addition to ensuring proper first-layer adhesion and reducing warping, should also be set to prevent denaturation of bioactive entities.

One further challenge is minimizing the need for post-processing, as many bioactive components are sensitive to chemical or mechanical treatments. Excessive post-processing can reduce the bioactivity of embedded agents or compromise the material's biocompatibility. Hence, optimized post-processing is required [298,299]. Bioactive filaments used in applications such as implants and scaffolds must exhibit sufficient mechanical strength [300]. Therefore, process parameters optimization may be needed. For instance, higher infill densities and optimized extrusion temperatures [301–303] can improve the

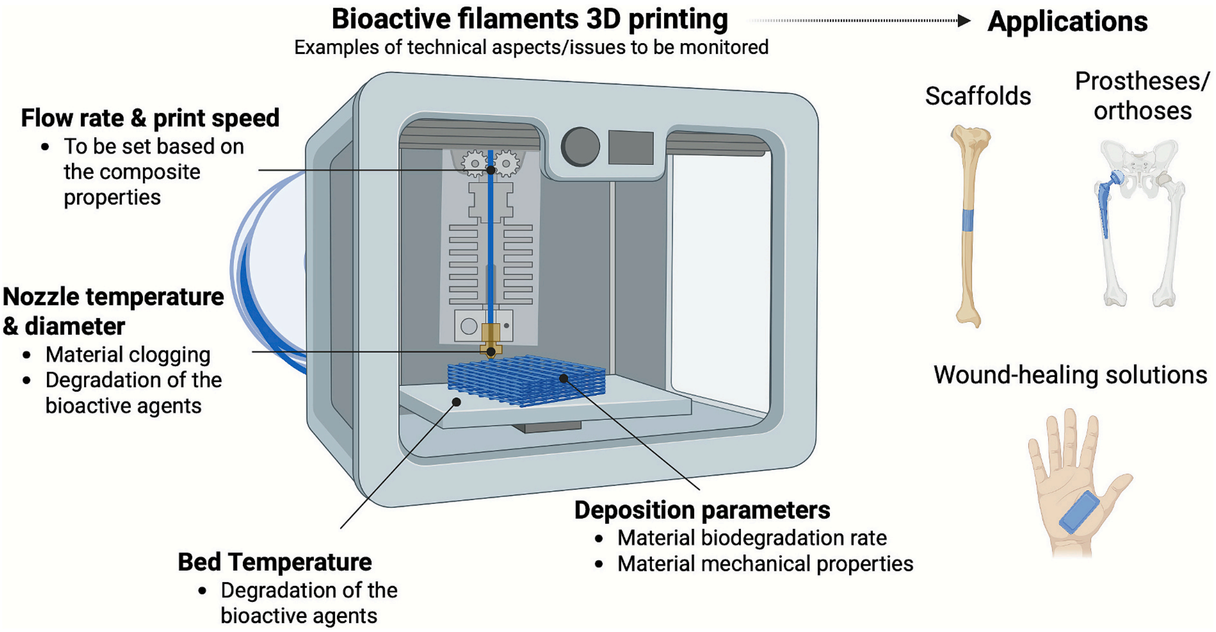

**Fig. 6.** An overview of some printing parameters that could affect the functionality and mechanical properties of 3D-printed bioactive devices/artifacts. Examples of potential applications are also represented (e.g., scaffolds, prostheses, and wound-healing solutions). Created in BioRender. Graziosi, S. (2026) https://BioRender.com/2qr2z3w.

**Table 3**
A summary of some studies demonstrating how AI can improve FDM 3D printing.

| Use Case | Model | Objective / Challenge Addressed | Key features | Ref |
|---|---|---|---|---|
| Deep learning for infill pattern defect detection | Convolutional Neural Network (CNN) | Real-time defect detection during FDM printing | Achieved 84 % accuracy with 50 epochs; paused print during detected anomalies to prevent material waste | [330] |
| Deep learning for warp detection | Convolutional Neural Network (CNN) | Warping detection during printing | Developed a closed-loop system with 99.3 % average accuracy in predicting corner distortion | [331] |
| Optical imaging and IR thermography | Convolutional Neural Network (CNN) | Detection of embedded defects (e.g., point and line defects) | Surface and subsurface defect detection through optical and thermal profiling | [332] |
| Image-based quality inspection | Neural Network (NN), Support Vector Machine (SVM), Gradient Boosted Classifier (GBC) | Layer-wise quality monitoring | Gradient Boosted Classifier (GBC) achieved highest accuracy; addressed lighting and image quality issues | [333] |
| Supervised Machine learning surface defect detection | Ensemble Learning, Support Vector Machine (SVM), k-Nearest Neighbors (KNN), Random Forest (RF), Decision Tree (DT), Naive Bayes (NB) | Surface fault detection | Combined AlexNet with SVM to achieve 99.7 % accuracy for anomaly monitoring | [334] |
| Deep learning for delamination and warping | Convolutional Neural Network (CNN) | Detection of structural failures | Achieved 97.8 % validation and 91.0 % testing accuracy in detecting delamination | [335] |
| ChatGPT-assisted optimization for FDM | Chat Generative Pre-trained Transformer (ChatGPT) | Code debugging, optimization of printing parameters, and autonomous G-code generation | Enabled structured and context-sensitive problem-solving (e.g., warping, bed detachment, stringing); improved G-code outputs by correlating filament properties with optimal settings. | [316] |
| Text-to-3D printable structure generation | Natural Language Processing (NLP) combined with Vector-Quantized Generative Adversarial Network (VQ-GAN) | Automated design of complex 3D printable architectures from text prompt | Assigned weighted significance to keywords; generated mirrored 2D patterns stacked into 3D periodic structures, enabling rapid prototyping of architected and bioinspired materials | [321] |
| Prediction and optimization of mechanical performance (tensile strength, stiffness) in FDM using recycled PLA | Random Forest, Gradient Boosting Regression, ANN | Experimental dataset including layer thickness, infill density, annealing conditions, and mechanical test results of recycled PLA | Predicting optimal parameter selection enabling recycled PLA to reach performance comparable to virgin material | [327] |
| Real-time monitoring and classification of recycled filament quality (diameter, surface defects) during recyclebots extrusion | Statistical learning, anomaly detection models, potential CNNs for surface feature analysis | Continuous sensor stream from open-source filament diameter and surface irregularity monitoring system | Quality classification (acceptable vs. defective) of recycled filament; real-time correction signals for extrusion motors | [328] |
| Modeling degradation trajectories of recycled polymers across multiple reuse cycles | Regression models, ANN, degradation-trajectory learning models | Mechanical tests, rheology, crystallinity, SEM analysis, extrusion history across multiple cycles | Prediction of remaining useful life, optimal blending ratios of recycled and virgin polymer | [329] |

mechanical performance of scaffolds intended for bone regeneration. Bioactive filaments are often used as drug-delivery or tissue-engineering scaffolds that release growth factors or antimicrobial agents over time [77]. When bioactive filaments are used for environmental applications (e.g., bioremediation or eco-friendly product manufacturing), the process must account for the material's environmental exposure and sustainability [284]. Apart from printing concerns, bioactive compounds from biowastes pose challenges in their segregation and processing to obtain the desired compounds [304]. Therefore, optimizing processing parameters could effectively improve biomass utilization, thereby reducing costs and energy consumption.

Considering all these issues is key. The intent to pursue research in the field of bioactive materials/filaments is strongly driven by the proper selection of the functional element to be considered, hopefully leveraging biomass waste where possible, the proper polymeric matrix (potentially obtained from recycling), and the adequate optimization of both the materials' manufacturing and printing phases. In addition, the recyclability of the 3D-printed artifacts manufactured with these filaments and their reuse are additional topics of investigation.

## 4. How Artificial Intelligence is contributing to material and process innovation in FDM

This last Section is dedicated to deepening the role AI and generative AI (GenAI) models can play in supporting efficient and novel plastic upcycling strategies through MEX, with a summary of available studies relevant to this target provided in Table 3.

These models can help address the need for more advanced controls and process optimization, which are fundamental aspects of manufacturing [305]. And since processing and printing parameters depend on the materials used, the search for novel compositions should go hand in hand with the development of process optimization strategies [306]. Besides, AI is emerging as a powerful enabler not only for optimizing print quality but also for helping reconcile sustainability with performance, enabling the recycling and reuse of polymer feedstocks to support a more circular economy. All these considerations are discussed as follows.

AI is already providing techniques and strategies for exploring and developing novel functional materials [307–310] while Generative AI is supporting not only material innovation but also process optimization, and precision in AM [311–314]. Through Natural Language Processing (NLP) and LLMs, researchers can analyze vast datasets to design new materials with tailored characteristics, reducing effort. LLMs can also help predict the printing performance of materials under specific conditions, ensuring suitability for the intended application [315–317]. These capabilities can be highly instrumental for MEX workflows focused on upcycling targets.

Indeed, conventionally, MEX and, especially, FDM tend to face numerous printing challenges [318,319], which lead to inconsistent layer deposition, warping due to thermal inconsistencies, material wastage, and limitations in achieving the desired accuracy for complex geometries. With novel and unconventional composite blends, these challenges can be even more exacerbated. Open issues related to ensuring proper layer adhesion and surface quality remain the least well-solved, even though ongoing research and technological improvements are progressively addressing them [275]. Even minor fluctuations in environmental conditions, such as humidity or temperature, can affect print quality, leading to failures or defects that require time-consuming rework. In that case, real-time data monitoring and processing, supported by AI, could prevent inconsistencies, save time, and, in turn, money [320].

For example, Badini et al. [316] investigated the application of Chat Generative Pre-trained Transformer (ChatGPT) in AM workflows, focusing on code manipulation, debugging, and tuning of printing parameters. The study [316] highlighted ChatGPT's potential to address common 3D printing challenges, such as warping, bed detachment, and stringing, by providing hierarchical, logically organized responses [316]. Considering this possibility, one could also fine-tune printing parameters for various filament types by correlating their mechanical properties with the appropriate printing settings. The authors trained ChatGPT on non-optimized G-code data to generate improved, problem-avoidant G-code outputs and evaluated the model's capacity to autonomously handle advanced technical tasks by prompting it to generate a fully optimized G-code from scratch [316].

In another study, Hsu et al. [321] developed a method to convert human-readable text into 3D printable material by combining natural language processing with a vector-quantized GAN. From a single text input, a 2D image is generated, mirrored, and stacked to form a 3D periodic structure, which is converted into a printable geometry. This approach [321] supports rapid prototyping and iterative design by translating abstract concepts into manufacturable digital models. It is particularly effective for streamlining the development of architected and bioinspired materials, enabling the creation of complex, multi-scale unit cells at reduced computational cost [321].

A study by Elbadawi et al. [322] explores the potential of conditional generative adversarial networks (cGANs) for generating novel, realistic material compositions. Working on optimizing FDM printing parameters and their effect on tensile strength, Wei et al. [323] reported that increasing the infill density reduces air gaps, ultimately contributing to enhancing tensile strength. They developed a model that predicts the tensile strength of FDM-printed specimens. Veeman et al. [324] employed linear regression, decision tree, random forest, and AdaBoost as machine learning models to optimize printing parameters such as infill density, layer thickness, print orientation, and raster orientation and predict hardness to understand its relationship to real-time data for the hardness values; they found the random forest model to produce efficient outcomes resulting in enhanced hardness. To understand the effect of printing parameters on the surface quality of FDM printed parts, Zhu et al. [325] utilized a combination of Transfer Learning (TL)-based Feature Extractor (FE) and Gradient-Boosting Decision Trees (GBDT). Brion et al. [326] developed a combined approach that includes deep learning, computer vision, and expert heuristics for auto-correction to prevent warping issues during printing.

A recent study demonstrates that ML can also forecast how process variables such as layer thickness, infill density, and post-print annealing affect the tensile strength and stiffness of parts made from recycled PLA, identifying optimal settings that bring the performance of recycled PLA close to that of virgin material [327]. This predictive capability could be transformative, as AI models of the interplay between printing parameters and material behavior help bridge the performance gap between recycled and virgin polymers.

Besides, recycling is also about preserving and guaranteeing feedstock quality. Distributed recycling systems, often built around small-scale “recyclebots”, face a persistent challenge: the recycled filament can vary widely in diameter, surface smoothness, or even micro-defects, depending on feedstock contamination or process drift. Here, AI and data-driven analytics can help in treating data extracted from sensors. For instance, an open-source 3D filament-diameter sensor has been developed, capable of tracking diameter fluctuations and spool-wise surface irregularities during re-extrusion of recycled materials [328]. As this sensor streams data over time, ML algorithms could analyze the patterns, detect deviations, and classify filament quality. This might mean separating spools suitable for high-performance applications from those with defects, or that could be used in less-critical applications, or triggering real-time motor adjustments to correct filament extrusion.

Moreover, the benefits of AI go further when multiple reuse cycles of polymeric materials are involved. Indeed, every time a recycled filament is printed, tested, and potentially reprocessed, degradation accumulates since molecular chains break, crystallinity may change, and mechanical properties shift. By collecting data across such cycles (i.e., mechanical test results, rheology, crystallography, scanning electron microscopy, sensor-derived filament history), AI models can learn degradation trajectories [329]. These systems could predict the remaining useful life of a spool, propose optimal blending strategies (i.e., mixing aged recycled filament with virgin polymer), or suggest process parameter adjustments (e.g., reducing print speed, increasing nozzle temperature, increase extrusion multiplier, decrease retraction distance) to mitigate performance loss, moving towards the creation of intelligent manufacturing systems that are capable of self-learning.

Ultimately, researchers need to investigate how to improve the interpretability of AI models and give operators easily usable, practical insights. Additionally, as recently highlighted by Pugliese et al. [309], a relevant but often overlooked challenge in integrating AI into AM and materials science is its environmental impact. Training GenAI systems requires vast computational resources, resulting in energy consumption and carbon emissions that far exceed those of conventional data center operations [309]. This impact conflicts with the sustainability and efficiency goals that AM aims to pursue. Addressing this paradox requires actions at multiple levels, from prioritizing energy-efficient algorithms and promoting green data centers powered by renewable energy to designing architectures that minimize computational overhead. Comprehensive lifecycle assessments of AI-assisted AM, from model training through production to end use, are therefore also fundamental to ensuring that technological advancements in AI align with environmental sustainability targets.

Collectively, these works (see also Table 3) underscore the growing role of AI in FDM and more generally in MEX, emphasizing its potential to enhance reliability, build user trust, and enable more effective human–AI collaboration.

## 5. Conclusions

This study has examined the upcycling potential of the MEX process – focusing specifically on FDM and FGF – as a potential contributor towards more circular, resource-efficient manufacturing. These AM techniques are driving relevant scientific developments in material innovations and process optimization, serving as fundamental building blocks for establishing effective circular chains. By analyzing the evolution of MEX technologies, advances in filament fabrication, the valorization of plastic and biomass waste, and the emerging role of AI, a broader picture of how extrusion-based AM can contribute to circularity is provided.

The study highlights how the affordability, flexibility, and continual technological refinement of FDM-related technologies have stimulated rapid innovation in material development, including biodegradable polymers, waste-derived composites, and, more recently, bioactive and bio-functional filaments. The expansion of desktop filament extruders and the parallel development of pellet-based FGF systems have opened new opportunities for experimenting with recycled polymers and heterogeneous waste streams, enabling both material upcycling and reduced reliance on virgin feedstocks. The design freedom enabled by AM is also key to envisioning new products that can further valorize these efforts.

In parallel, examples of biomass-derived fillers and bioactive compounds illustrate how agricultural and food-processing waste can be transformed into functional additives, reducing plastic use while offering mechanical, chemical, or therapeutic benefits. This area remains the least explored in research, whose harnessing could lead to functional 3D-printable materials for low-cost solutions in the health sector and help reduce biomass disposal, a major environmental issue. However, it also poses new challenges, including potential declines in mechanical strength and variability in the 3D printing process, which require optimized parameters, surface finishing, and cost-effective waste segregation and processing.

At the same time, the integration of AI and ML into MEX workflows is accelerating progress in material discovery, print-parameter optimization, defect detection, and prediction of recycled-material performance. These tools are increasingly capable of mitigating the inherent variability of recycled feedstocks, improving print reliability, and supporting distributed recycling ecosystems. As such, AI does not simply optimize performance, but it becomes a strategic ally in reconciling sustainability targets with manufacturability and quality.

However, several limitations remain. Despite the variety of examples discussed, the analysis in this review is intentionally restricted to MEX (in particular, FDM, FGF, and other MEX variants). Other AM approaches (and related materials), such as vat photopolymerization, powder-bed fusion, or direct ink writing, also contribute to sustainable materials research and waste valorization [336–338], but they fall outside the scope of this study.

Moreover, other key technical barriers persist. Recycled polymers often exhibit variability and degraded mechanical performance; biomass fillers may compromise printability or consistency; bioactive compounds require strict thermal and process control; and biodegradable polymers do not always degrade efficiently in real-world conditions. Furthermore, FDM and FGF still face scalability limitations, especially relative to conventional mass-manufacturing techniques, and require more mature industrial frameworks to ensure consistent quality, material traceability, and economically and environmentally sustainable recycling workflows.

Despite these challenges, the evidence reviewed suggests that MEX has significant potential to support more sustainable production models when combined with informed material design, responsible process optimization, and AI-enabled decision-making. Hence, this study highlights that, despite the numerous studies already available, the research landscape appears to be full of still-unexplored challenges and opportunities to enhance the upcycling potential of MEX and strengthen the role of AM in the circular economy paradigm, but the potential is there. Continued interdisciplinary research – spanning materials science, biotechnology, process engineering, AI, and product design – will be crucial for unlocking this potential by envisioning and developing novel applications that promote MEX as a credible pathway toward a more circular and eco-efficient manufacturing ecosystem.

## CRediT authorship contribution statement

**Raffaele Pugliese:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Mushtaq Alam Madar Saheb:** Writing – review & editing, Writing – original draft, Investigation. **Stefano Cantella:** Writing – review & editing, Writing – original draft, Investigation. **Silvia Badini:** Writing – review & editing, Writing – original draft, Investigation. **Carlotta Bollati:** Writing – review & editing, Writing – original draft, Investigation. **Carmen Lammi:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Serena Graziosi:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

## 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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## Data availability

No data was used for the research described in the article.

## References

[1] K. Lee, Y. Jing, Y. Wang, N. Yan, A unified view on catalytic conversion of biomass and waste plastics, Nat. Rev. Chem. 6 (2022) 635–652, https://doi.org/10.1038/s41570-022-00411-8.

[2] L.T.J. Korley, T.H. Epps, B.A. Helms, A.J. Ryan, Toward polymer upcycling—adding value and tackling circularity, Science 373 (2021) (1979) 66–69, https://doi.org/10.1126/science.abg4503.

[3] On the plastics crisis, Nat Sustain 6 (2023) 1137, https://doi.org/10.1038/s41893-023-01236-z.

[4] OECD, Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD Publishing, Paris, 2022. doi:10.1787/de747aef-en.

[5] M. Bachmann, C. Zibunas, J. Hartmann, V. Tulus, S. Suh, G. Guillén-Gosálbez, A. Bardow, Towards circular plastics within planetary boundaries, Nat Sustain 6 (2023) 599–610, https://doi.org/10.1038/s41893-022-01054-9.

[6] V.G. Zuin, K. Kümmerer, Chemistry and materials science for a sustainable circular polymeric economy, Nat. Rev. Mater. 7 (2022) 76–78, https://doi.org/10.1038/s41578-022-00415-2.

[7] Nat Catal 2 (2019) 945–946, https://doi.org/10.1038/s41929-019-0391-7.

[8] X. Zhao, B. Boruah, K.F. Chin, M. Đokić, J.M. Modak, H., Sen Soo, Upcycling to Sustainably Reuse Plastics, Adv. Mater. 34 (2022) 2100843, https://doi.org/10.1002/adma.202100843.

[9] C. Jehanno, J.W. Alty, M. Roosen, S. De Meester, A.P. Dove, E.-Y.-X. Chen, F. A. Leibfarth, H. Sardon, Critical advances and future opportunities in upcycling commodity polymers, Nature 603 (2022) 803–814, https://doi.org/10.1038/s41586-021-04350-0.

[10] S. Yang, Y. Li, M. Nie, X. Liu, Q. Wang, N. Chen, C. Zhang, Lifecycle Management for Sustainable Plastics: recent Progress from Synthesis, Processing to Upcycling, Advanced Materials 36 (2024) 2404115, https://doi.org/10.1002/adma.202404115.

[11] M.R. Karimi Estahbanati, X.Y. Kong, A. Eslami, H. Sen Soo, Current Developments in the Chemical Upcycling of Waste Plastics using Alternative Energy sources, ChemSusChem 14 (2021) 4152–4166, https://doi.org/10.1002/cssc.202100874.

[12] ISO/ASTM 52900:2021, Additive Manufacturing — General Principles — Fundamentals and Vocabulary (2021).

[13] A. Patti, Challenges to Improve Extrusion-Based Additive Manufacturing Process of Thermoplastics toward Sustainable Development, Macromol. Rapid Commun. 45 (2024) 2400249, https://doi.org/10.1002/marc.202400249.

[14] M.L. Lepage, J.E. Wulff, Mixed plastics upcycled dynamically, Nature 616 (2023) 663–664, https://doi.org/10.1038/d41586-023-01352-y.

[15] O. Francioso, Current and future perspectives for biomass waste management and utilization, Sci. Rep. 14 (2024) 9635, https://doi.org/10.1038/s41598-024-59623-1.

[16] J. Frigerio, S. Bertacchi, S. Mecca, S. Digiovanni, T. Molteni, V. Mapelli, L. Beverina, M. Lotti, E. Croci, P. Branduardi, M. Labra, From urban trash to city cash: Technologies for sustainable development of cities through the valorisation of urban organic waste in Europe, Waste Management Bulletin 3 (2025) 100222, https://doi.org/10.1016/j.wmb.2025.100222.

[17] S. Kumar, S.K. Lohan, D.S. Parihar, Biomass Energy from Agriculture, in: A. Rakshit, A. Biswas, D. Sarkar, V.S. Meena, R. Datta (Eds.), Handbook of Energy Management in Agriculture, Springer Nature Singapore, Singapore, 2023: pp. 181–199. doi:10.1007/978-981-19-7736-7_10-1.

[18] M. Yang, L. Chen, J. Wang, G. Msigwa, A.I. Osman, S. Fawzy, D.W. Rooney, P.-S. Yap, Circular economy strategies for combating climate change and other environmental issues, Environ. Chem. Lett. 21 (2023) 55–80, https://doi.org/10.1007/s10311-022-01499-6.

[19] M. Saleem, Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source, Heliyon 8 (2022) e08905, https://doi.org/10.1016/j.heliyon.2022.e08905.

[20] A. Cano-Vicent, M.M. Tambuwala, S. Sk, D. Hassan, A.A.A. Barh, M. Aljabali, A. Birkett, Á.-A. Arjunan, Fused Deposition Modelling: Current Status, Methodology, Applications and Future Prospects, Addit Manuf 47 (2021) 102378, https://doi.org/10.1016/j.addma.2021.102378.

[21] X. Sun, M. Mazur, C.-T. Cheng, A review of void reduction strategies in material extrusion-based additive manufacturing, Addit. Manuf. 67 (2023) 103463, https://doi.org/10.1016/j.addma.2023.103463.

[22] F. Tamburrino, S. Graziosi, M. Bordegoni, The influence of slicing parameters on the multi-material adhesion mechanisms of FDM printed parts: an exploratory study, Virtual Phys Prototyp 14 (2019) 316–332, https://doi.org/10.1080/17452759.2019.1607758.

[23] A. Gleadall, FullControl GCode designer: Open-source software for unconstrained design in additive manufacturing, Addit. Manuf. 46 (2021) 102109, https://doi.org/10.1016/j.addma.2021.102109.

[24] S.C. Daminabo, S. Goel, S.A. Grammatikos, H.Y. Nezhad, V.K. Thakur, Fused deposition modeling-based additive manufacturing (3D printing): techniques for polymer material systems, Mater. Today Chem. 16 (2020) 100248, https://doi.org/10.1016/j.mtchem.2020.100248.

[25] M. Javaid, A. Haleem, R.P. Singh, R. Suman, E.S. Gonzalez, Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability, Sustainable Operations and Computers 3 (2022) 203–217, https://doi.org/10.1016/j.susoc.2022.01.008.

[26] D. Popescu, A. Zapciu, C. Amza, F. Baciu, R. Marinescu, FDM process parameters influence over the mechanical properties of polymer specimens: a review, Polym. Test. 69 (2018) 157–166, https://doi.org/10.1016/j.polymertesting.2018.05.020.

[27] A. Sola, W.J. Chong, D. Pejak Simunec, Y. Li, A. Trinchi, I. (Louis) Kyratzis, C. Wen, Open challenges in tensile testing of additively manufactured polymers: A literature survey and a case study in fused filament fabrication, Polym Test 117 (2023) 107859. doi:10.1016/j.polymertesting.2022.107859.

[28] A. Kantaros, T. Ganetsos, F. Petrescu, L. Ungureanu, I. Munteanu, Post-Production Finishing Processes Utilized in 3D Printing Technologies, Processes 12 (2024) 595, https://doi.org/10.3390/pr12030595.

[29] M.E. Prendergast, J.A. Burdick, Recent advances in Enabling Technologies in 3D Printing for Precision Medicine, Adv. Mater. 32 (2020) 1902516, https://doi.org/10.1002/adma.201902516.

[30] L. Suárez, M. Domínguez, Sustainability and environmental impact of fused deposition modelling (FDM) technologies, Int. J. Adv. Manuf. Technol. 106 (2020) 1267–1279, https://doi.org/10.1007/s00170-019-04676-0.

[31] Y. Shi, J. Faludi, Using life cycle assessment to determine if high utilization is the dominant force for sustainable polymer additive manufacturing, Addit. Manuf. 35 (2020) 101307, https://doi.org/10.1016/j.addma.2020.101307.

[32] V. Mishra, S. Negi, S. Kar, FDM-based additive manufacturing of recycled thermoplastics and associated composites, J Mater Cycles Waste Manag 25 (2023) 758–784, https://doi.org/10.1007/s10163-022-01588-2.

[33] M. Korey, M.L. Rencheck, H. Tekinalp, S. Wasti, P. Wang, S. Bhagia, R. Walker, T. Smith, X. Zhao, M.E. Lamm, K. Copenhaver, U. Vaidya, S. Ozcan, Recycling polymer composite granulate/regrind using big area additive manufacturing, Compos. B Eng. 256 (2023) 110652, https://doi.org/10.1016/j.compositesb.2023.110652.

[34] A. Romani, M. Levi, J.M. Pearce, Recycled polycarbonate and polycarbonate/acrylonitrile butadiene styrene feedstocks for circular economy product applications with fused granular fabrication-based additive manufacturing, Sustain. Mater. Technol. 38 (2023) e00730, https://doi.org/10.1016/j.susmat.2023.e00730.

[35] A. Curmi, A. Rochman, Screw extrusion fused granulate Fabrication: Trends, materials, extruder classification and future development, Polymer (guildf) 330 (2025) 128459, https://doi.org/10.1016/j.polymer.2025.128459.

[36] P. Burgos Pintos, P. Marzo Gago, N. Fernández Delgado, M. Herrera, A. Sanz De León, S.I. Molina, Sustainable product design by large format additive manufacturing of cork composites, Virtual Phys Prototyp 19 (2024) e2386106, https://doi.org/10.1080/17452759.2024.2386106.

[37] P. Awasthi, S.S. Banerjee, Fused deposition modeling of thermoplastic elastomeric materials: challenges and opportunities, Addit. Manuf. 46 (2021) 102177, https://doi.org/10.1016/j.addma.2021.102177.

[38] N. Willemstein, M.E. Imanian, H. van der Kooij, A. Sadeghi, Pellet-based 3D printing of soft thermoplastic elastomeric membranes for soft robotic applications, Mater. Des. 258 (2025) 114589, https://doi.org/10.1016/j.matdes.2025.114589.

[39] P. Burgos Pintos, A. Sanz de León, S.I. Molina, Large format additive manufacturing of polyethylene terephthalate (PET) by material extrusion, Addit. Manuf. 79 (2024) 103908, https://doi.org/10.1016/j.addma.2023.103908.

[40] S. Liu, P. Zhao, S. Wu, C. Zhang, J. Fu, Z. Chen, A Pellet 3D Printer: Device Design and Process Parameters Optimization, Adv. Polym. Tech. 2019 (2019) 1–8, https://doi.org/10.1155/2019/5075327.

[41] E. Bilal, Y.R. Glazer, D.M. Sassaman, C.C. Seepersad, M.E. Webber, Circularity: Understanding the Environmental Tradeoffs of Additive Manufacturing with Waste Plastics, Recycling 9 (2024), https://doi.org/10.3390/recycling9050072.

[42] J.M. Justino Netto, H.T. Idogava, L.E. Frezzatto Santos, Z. de C. Silveira, P. Romio, J.L. Alves, Screw-assisted 3D printing with granulated materials: a systematic review, The International Journal of Advanced Manufacturing Technology 115 (2021) 2711–2727. doi:10.1007/s00170-021-07365-z.

[43] O.B. Carcassi, L. Ben-Alon, Additive manufacturing of natural materials, Autom. Constr. 167 (2024) 105703, https://doi.org/10.1016/j.autcon.2024.105703.

[44] AMPOWER, Polymer Additive Manufacturing technology landscape, (2025). https://ampower.eu/infographics/polymer-additive-manufacturing/ (accessed December 4, 2025).

[45] S. Graziosi, J. Faludi, T. Stanković, Y. Borgianni, N. Meisel, S.I. Hallstedt, D. W. Rosen, A vision for sustainable additive manufacturing, Nat Sustain 7 (2024) 698–705, https://doi.org/10.1038/s41893-024-01313-x.

[46] C.S. Gonzalez, A. Basdeo, F.A. Cruz Sanchez, C. Nouvel, J.M. Pearce, H. Boudaoud, Strategies for recycling multi-material polymer blends for additive manufacturing, Sustain. Mater. Technol. 44 (2025) e01430, https://doi.org/10.1016/j.susmat.2025.e01430.

[47] S. Bhagia, K. Bornani, R. Agrawal, A. Satlewal, J. Ďurkovič, R. Lagaňa, M. Bhagia, C.G. Yoo, X. Zhao, V. Kunc, Y. Pu, S. Ozcan, A.J. Ragauskas, Critical review of FDM 3D printing of PLA biocomposites filled with biomass resources, characterization, biodegradability, upcycling and opportunities for biorefineries, Appl. Mater. Today 24 (2021) 101078, https://doi.org/10.1016/j.apmt.2021.101078.

[48] A. Sola, R. Rosa, A.M. Ferrari, Environmental Impact of Fused Filament Fabrication: what is known from Life Cycle Assessment? Polymers (basel) 16 (2024) 1986, https://doi.org/10.3390/polym16141986.

[49] Y.B. Siyoum, F.G. Kindie, M.A. Gebeyehu, A review of current research and prospects of fused deposition modelling: application, materials, performance, process variables, parameter optimization, and numerical study, Int. J. Adv.

Manuf. Technol. 138 (2025) 1675–1711, https://doi.org/10.1007/s00170-025-15615-7.

[50] J.P. Rett, Y.L. Traore, E.A. Ho, Sustainable Materials for Fused Deposition Modeling 3D Printing applications, Adv. Eng. Mater. 23 (2021) 2001472, https://doi.org/10.1002/adem.202001472.

[51] M. Hassan, A.K. Mohanty, M. Misra, 3D printing in upcycling plastic and biomass waste to sustainable polymer blends and composites: a review, Mater. Des. 237 (2024) 112558, https://doi.org/10.1016/j.matdes.2023.112558.

[52] Z. Yang, J. Li, Y. Guo, Y. Wang, W. Zhao, W. Zhao, Y. Liu, L. Zhang, Biomass materials and their application in 4D printing, International Journal of Extreme Manufacturing 7 (2025) 052003, https://doi.org/10.1088/2631-7990/add81c.

[53] D.W. Rosen, The Current Design for Additive Manufacturing Research Frontier, Int. J. Precis. Eng. Manuf.-Smart Tech. 2 (2024) 1–14, https://doi.org/10.57062/ijpem-st.2023.0087.

[54] H. Garcia-Gonzalez, T. Lopez-Pola, P. Fernandez-Rubio, P. Fernandez-Rodriguez, Analysis of Volatile Organic compound Emissions in 3D Printing: Implications for Indoor Air Quality, Buildings 14 (2024), https://doi.org/10.3390/buildings14113343.

[55] V. Shanmugam, K. Babu, G. Kannan, R.A. Mensah, S.K. Samantaray, O. Das, The thermal properties of FDM printed polymeric materials: a review, Polym. Degrad. Stab. 228 (2024) 110902, https://doi.org/10.1016/j.polymdegradstab.2024.110902.

[56] A. Patel, M. Taufik, Extrusion-based Technology in Additive Manufacturing: a Comprehensive Review, Arab. J. Sci. Eng. 49 (2024) 1309–1342, https://doi.org/10.1007/s13369-022-07539-1.

[57] T. Pepelnjak, J. Stojšić, L. Sevšek, D. Movrin, M. Milutinović, Influence of Process Parameters on the Characteristics of Additively Manufactured Parts made from Advanced Biopolymers, Polymers (basel) 15 (2023) 716, https://doi.org/10.3390/polym15030716.

[58] A. Smirnov, N. Nikitin, P. Peretyagin, R. Khmyrov, E. Kuznetsova, N.W. Solis Pinargote, Experimental and Statistical Modeling for effect of Nozzle Diameter, filling Pattern, and Layer Height of FDM-Printed Ceramic–Polymer Green Body on Biaxial Flexural Strength of Sintered Alumina Ceramic, Journal of Composites Science 7 (2023) 381, https://doi.org/10.3390/jcs7090381.

[59] D. Frunzaverde, V. Cojocaru, N. Bacescu, C.-R. Ciubotariu, C.-O. Miclosina, R. R. Turiac, G. Marginean, The Influence of the Layer Height and the Filament Color on the Dimensional Accuracy and the Tensile Strength of FDM-Printed PLA Specimens, Polymers (basel) 15 (2023) 2377, https://doi.org/10.3390/polym15102377.

[60] T. Ritter, E. McNiffe, T. Higgins, O. Sam-Daliri, T. Flanagan, M. Walls, P. Ghabezi, W. Finnegan, S. Mitchell, N.M. Harrison, Design and Modification of a Material Extrusion 3D Printer to Manufacture Functional Gradient PEEK Components, Polymers (basel) 15 (2023) 3825, https://doi.org/10.3390/polym15183825.

[61] Y.G. Mittal, Y. Patil, P.P. Kamble, G.D. Gote, A.K. Mehta, K.P. Karunakaran, Warpage control in thermoplastic ABS parts produced through material extrusion (MEX)-based fused deposition modeling (FDM), Rapid Prototyp. J. 30 (2024) 1822–1835, https://doi.org/10.1108/RPJ-01-2024-0023.

[62] Z. Qi, Z. Xu, F. Li, C. Yao, Effect of cooling strategy on the bearing capacity of CF/PEEK composite hole, Compos. B Eng. 250 (2023) 110406, https://doi.org/10.1016/j.compositesb.2022.110406.

[63] S. Thumsorn, W. Prasong, A. Ishigami, T. Kurose, Y. Kobayashi, H. Ito, Influence of Ambient Temperature and Crystalline Structure on Fracture Toughness and production of Thermoplastic by Enclosure FDM 3D Printer, Journal of Manufacturing and Materials Processing 7 (2023) 44, https://doi.org/10.3390/jmmp7010044.

[64] M. Khalid, Q. Peng, Investigation of Printing Parameters of Additive Manufacturing Process for Sustainability using Design of Experiments, J. Mech. Des. 143 (2021) 032001, https://doi.org/10.1115/1.4049521.

[65] S.K. Mangla, Y. Kazancoglu, M.D. Sezer, N. Top, I. Sahin, Optimizing fused deposition modelling parameters based on the design for additive manufacturing to enhance product sustainability, Comput. Ind. 145 (2023) 103833, https://doi.org/10.1016/j.compind.2022.103833.

[66] V. Mishra, C.H.K. Ror, S. Negi, S. Kar, L.N. Borah, 3D printing with recycled ABS resin: effect of blending and printing temperature, Mater. Chem. Phys. 309 (2023) 128317, https://doi.org/10.1016/j.matchemphys.2023.128317.

[67] S.J. Park, J.E. Lee, J. Park, N.-K. Lee, Y. Son, S.-H. Park, High-temperature 3D printing of polyetheretherketone products: Perspective on industrial manufacturing applications of super engineering plastics, Mater. Des. 211 (2021) 110163, https://doi.org/10.1016/j.matdes.2021.110163.

[68] F. Liu, C. Vyas, G. Poologasundarampillai, I. Pape, S. Hinduja, W. Mirihanage, P. Bartolo, Structural Evolution of PCL during Melt Extrusion 3D Printing, Macromol. Mater. Eng. 303 (2018) 1700494, https://doi.org/10.1002/mame.201700494.

[69] B. Wittbrodt, J.M. Pearce, The effects of PLA color on material properties of 3-D printed components, Addit. Manuf. 8 (2015) 110–116, https://doi.org/10.1016/j.addma.2015.09.006.

[70] L. De Bernardez, G. Campana, M. Mele, J. Sanguineti, C. Sandre, S.M. Mur, Effects of infill patterns on part performances and energy consumption in acrylonitrile butadiene styrene fused filament fabrication via industrial-grade machine, Prog. Addit. Manuf. 8 (2023) 117–129, https://doi.org/10.1007/s40964-022-00316-4.

[71] G. Tedla, A.M. Jarabek, P. Byrley, W. Boyes, K. Rogers, Human exposure to metals in consumer-focused fused filament fabrication (FFF)/ 3D printing processes, Sci. Total Environ. 814 (2022) 152622, https://doi.org/10.1016/j.scitotenv.2021.152622.

[72] D. Acierno, A. Patti, Fused Deposition Modelling (FDM) of Thermoplastic-based Filaments: Process and Rheological Properties—An Overview, Materials 16 (2023) 7664, https://doi.org/10.3390/ma16247664.

[73] M.N. Andanje, J.W. Mwangi, B.R. Mose, S. Carrara, Biocompatible and Biodegradable 3D Printing from Bioplastics: a Review, Polymers (basel) 15 (2023) 2355, https://doi.org/10.3390/polym15102355.

[74] E.M. Palmero, J. Rial, J. De Vicente, J. Camarero, B. Skårman, H. Vidarsson, P.-O. Larsson, A. Bollero, Development of permanent magnet MnAlC/polymer composites and flexible filament for bonding and 3D-printing technologies, Sci. Technol. Adv. Mater. 19 (2018) 465–473, https://doi.org/10.1080/14686996.2018.1471321.

[75] C.G. Schirmeister, T. Hees, E.H. Licht, R. Mülhaupt, 3D printing of high density polyethylene by fused filament fabrication, Addit. Manuf. 28 (2019) 152–159, https://doi.org/10.1016/j.addma.2019.05.003.

[76] S.W. Kwok, K.H.H. Goh, Z.D. Tan, S.T.M. Tan, W.W. Tjiu, J.Y. Soh, Z.J.G. Ng, Y. Z. Chan, H.K. Hui, K.E.J. Goh, Electrically conductive filament for 3D-printed circuits and sensors, Appl. Mater. Today 9 (2017) 167–175, https://doi.org/10.1016/j.apmt.2017.07.001.

[77] J. Wang, Y. Wang, R. Wang, Q. Wang, M. Wen, J. Wang, L. Sheng, Y. Zheng, T. Xi, A Review on 3D Printing Processes in Pharmaceutical Engineering and Tissue Engineering: applications, Trends and Challenges, Adv Mater Technol 10 (2025) 2400620, https://doi.org/10.1002/admt.202400620.

[78] A. Dubey, H. Vahabi, V. Kumaravel, Antimicrobial and Biodegradable 3D Printed Scaffolds for Orthopedic Infections, ACS Biomater Sci. Eng. 9 (2023) 4020–4044, https://doi.org/10.1021/acsbiomaterials.3c00115.

[79] N.C. Paxton, J. Zhao, E. Sauret, Polymer 3D printing in perspective: Assessing challenges and opportunities in industrial translation against the metal benchmark, Int. J. Adv. Manuf. Technol. 133 (2024) 59–80, https://doi.org/10.1007/s00170-024-13744-z.

[80] S. Vennam, V. Kn, F. Pati, 3D printed personalized assistive devices: a material, technique, and medical condition perspective, Appl. Mater. Today 40 (2024) 102403, https://doi.org/10.1016/j.apmt.2024.102403.

[81] F. Rezaie, M. Farshbaf, M. Dahri, M. Masjedi, R. Maleki, F. Amini, J. Wirth, K. Moharamzadeh, F.E. Weber, L. Tayebi, 3D Printing of Dental Prostheses: current and Emerging applications, Journal of Composites Science 7 (2023) 80, https://doi.org/10.3390/jcs7020080.

[82] S. Graziosi, S. Badini, C. Lammi, C. Bollati, S. Regondi, R. Pugliese, Biocompatible and soft micro/nanoporous 3D-printed scaffolds with superoleophilic/superadsorption capabilities, Appl. Mater. Today 45 (2025) 102853, https://doi.org/10.1016/j.apmt.2025.102853.

[83] P.K. Biswas, O. Omole, G. Peterson, E. Cumbo, M. Agarwal, H. Dalir, Carbon and cellulose based nanofillers reinforcement to strengthen carbon fiber-epoxy composites: Processing, characterizations, and applications, Front. Mater. 9–2022 (2023), https://doi.org/10.3389/fmats.2022.1089996.

[84] A.M. Rahman, T.T. Rahman, Z. Pei, C.O. Ufodike, J. Lee, A. Elwany, Additive Manufacturing using Agriculturally Derived Biowastes: a Systematic Literature Review, Bioengineering 10 (2023) 845, https://doi.org/10.3390/bioengineering10070845.

[85] A.M. Almushaikeh, S.O. Alaswad, M.S. Alsuhybani, B.M. AlOtaibi, I.M. Alarifi, N. B. Alqahtani, S.M. Aldosari, S.S. Alsaleh, A.S. Haidyrah, A.A. Alolyan, B. A. Alshammari, Manufacturing of carbon fiber reinforced thermoplastics and its recovery of carbon fiber: a review, Polym. Test. 122 (2023) 108029, https://doi.org/10.1016/j.polymertesting.2023.108029.

[86] S. Bergaliyeva, D.L. Sales, F.J. Delgado, S. Bolegenova, S.I. Molina, Manufacture and Characterization of Polylactic Acid Filaments Recycled from Real Waste for 3D Printing, Polymers (basel) 15 (2023) 2165, https://doi.org/10.3390/polym15092165.

[87] O. Okolie, A. Kumar, C. Edwards, L.A. Lawton, A. Oke, S. McDonald, V.K. Thakur, J. Njuguna, Bio-based Sustainable Polymers and Materials: from Processing to Biodegradation, Journal of Composites Science 7 (2023) 213, https://doi.org/10.3390/jcs7060213.

[88] Z. Piao, A.A. Agyei Boakye, Y. Yao, Environmental impacts of biodegradable microplastics, Nature Chemical Engineering 1 (2024) 661–669, https://doi.org/10.1038/s44286-024-00127-0.

[89] J. Lee, H. Lee, K.-H. Cheon, C. Park, T.-S. Jang, H.-E. Kim, H.-D. Jung, Fabrication of poly(lactic acid)/Ti composite scaffolds with enhanced mechanical properties and biocompatibility via fused filament fabrication (FFF)–based 3D printing, Addit. Manuf. 30 (2019) 100883, https://doi.org/10.1016/j.addma.2019.100883.

[90] T.K. Sinha, H.R. Chothe, J.H. Lim, J.G. Kim, T. Lee, T. Nam, J.S. Oh, Fabricating Efficient and Biocompatible Filament for Material Extrusion-based Low-cost Additive Manufacturing: a Case Study with Steel, J. Mater. Eng. Perform. 32 (2023) 1966–1973, https://doi.org/10.1007/s11665-022-07222-4.

[91] R. Sharma, R. Singh, R. Penna, F. Fraternali, Investigations for mechanical properties of Hap, PVC and PP based 3D porous structures obtained through biocompatible FDM filaments, Compos. B Eng. 132 (2018) 237–243, https://doi.org/10.1016/j.compositesb.2017.08.021.

[92] S. Graziosi, F.M. Ballo, F. Libonati, S. Senna, 3D printing of bending-dominated soft lattices: numerical and experimental assessment, Rapid Prototyp. J. 28 (2022) 51–64, https://doi.org/10.1108/RPJ-03-2022-0095.

[93] R. Sala, S. Regondi, S. Graziosi, R. Pugliese, Insights into the printing parameters and characterization of thermoplastic polyurethane soft triply periodic minimal surface and honeycomb lattices for broadening material extrusion applicability, Addit. Manuf. 58 (2022) 102976, https://doi.org/10.1016/j.addma.2022.102976.

[94] X. Hu, Y. Chen, W. Xu, Y. Zhu, D. Kim, Y. Fan, B. Yu, Y. Chen, 3D-Printed Thermoplastic polyurethane Electrodes for Customizable, Flexible Lithium-Ion Batteries with an Ultra-Long Lifetime, Small 19 (2023) 2301604, https://doi.org/10.1002/smll.202301604.

[95] A. Kantaros, E. Soulis, F.I.T. Petrescu, T. Ganetsos, Advanced Composite Materials Utilized in FDM/FFF 3D Printing Manufacturing Processes: the Case of Filled Filaments, Materials 16 (2023), https://doi.org/10.3390/ma16186210.

[96] O. Rashwan, Z. Koroneos, T.G. Townsend, M.P. Caputo, R.J. Bylone, B. Wodrig, K. Cantor, Extrusion and characterization of recycled polyethylene terephthalate (rPET) filaments compounded with chain extender and impact modifiers for material-extrusion additive manufacturing, Sci. Rep. 13 (2023) 16041, https://doi.org/10.1038/s41598-023-41744-8.

[97] A. Gopal, P. Patil, H. Pol, K. Shanmuganathan, Upcycling of Postconsumer Recyclate Polypropylene into Low Warping and High Toughness 3D Printable Filaments, ACS Appl. Polym. Mater. 7 (2025) 7373–7381, https://doi.org/10.1021/acsapm.5c00942.

[98] A. Nazir, O. Gokcekaya, K. Md Masum Billah, O. Ertugrul, J. Jiang, J. Sun, S. Hussain, Multi-material additive manufacturing: A systematic review of design, properties, applications, challenges, and 3D printing of materials and cellular metamaterials, Mater Des 226 (2023) 111661. doi:10.1016/j.matdes.2023.111661.

[99] F. Richter, D. Wu, Interfacial adhesion between dissimilar thermoplastics fabricated via material extrusion-based multi-material additive manufacturing, Mater. Des. 252 (2025) 113688, https://doi.org/10.1016/j.matdes.2025.113688.

[100] N.C. Brown, D.C. Ames, J. Mueller, Multimaterial extrusion 3D printing printheads, Nat. Rev. Mater. (2025), https://doi.org/10.1038/s41578-025-00809-y.

[101] M. Ozdemir, Z. Doubrovski, Foam2Form: 4D Printing with Programmable Foaming, in: Extended Abstracts of the CHI Conference on Human Factors in Computing Systems, Association for Computing Machinery, New York, NY, USA, 2024. doi:10.1145/3613905.3650869.

[102] M. Hosseinzadeh, M. Ghoreishi, K. Narooei, 4D printing of shape memory polylactic acid beams: an experimental investigation into FDM additive manufacturing process parameters, mathematical modeling, and optimization, J. Manuf. Process. 85 (2023) 774–782, https://doi.org/10.1016/j.jmapro.2022.12.006.

[103] K. Kanishka, B. Acherjee, Revolutionizing manufacturing: a comprehensive overview of additive manufacturing processes, materials, developments, and challenges, J. Manuf. Process. 107 (2023) 574–619, https://doi.org/10.1016/j.jmapro.2023.10.024.

[104] J.-G. Rosenboom, R. Langer, G. Traverso, Bioplastics for a circular economy, Nat. Rev. Mater. 7 (2022) 117–137, https://doi.org/10.1038/s41578-021-00407-8.

[105] E. Balla, V. Daniilidis, G. Karlioti, T. Kalamas, M. Stefanidou, N.D. Bikiaris, A. Vlachopoulos, I. Koumentakou, D.N. Bikiaris, Poly(lactic Acid): a Versatile Biobased Polymer for the Future with Multifunctional Properties—From Monomer Synthesis, Polymerization Techniques and Molecular Weight increase to PLA applications, Polymers (basel) 13 (2021) 1822, https://doi.org/10.3390/polym13111822.

[106] A.Z. Naser, I. Deiab, F. Defersha, S. Yang, Expanding Poly(lactic acid) (PLA) and Polyhydroxyalkanoates (PHAs) applications: a Review on modifications and Effects, Polymers (basel) 13 (2021), https://doi.org/10.3390/polym13234271.

[107] S. S, A.P. R G, G. Bajaj, A.E. John, S. Chandran, V.V. Kumar, S. Ramakrishna, A review on the recent applications of synthetic biopolymers in 3D printing for biomedical applications, J Mater Sci Mater Med 34 (2023) 62. doi:10.1007/s10856-023-06765-9.

[108] S. Choe, Y. Kim, G. Park, D.H. Lee, J. Park, A.T. Mossisa, S. Lee, J. Myung, Biodegradation of 3D-printed Biodegradable/Non-biodegradable Plastic Blends, ACS Appl. Polym. Mater. 4 (2022) 5077–5090, https://doi.org/10.1021/acsapm.2c00600.

[109] R.M. Cywar, N.A. Rorrer, C.B. Hoyt, G.T. Beckham, E.-Y.-X. Chen, Bio-based polymers with performance-advantaged properties, Nat. Rev. Mater. 7 (2022) 83–103, https://doi.org/10.1038/s41578-021-00363-3.

[110] T.M. Joseph, A. Kallingal, A.M. Suresh, D.K. Mahapatra, M.S. Hasanin, J. Haponiuk, S. Thomas, 3D printing of polylactic acid: recent advances and opportunities, Int. J. Adv. Manuf. Technol. 125 (2023) 1015–1035, https://doi.org/10.1007/s00170-022-10795-y.

[111] A.K. Trivedi, M.K. Gupta, PLA based biodegradable bionanocomposite filaments reinforced with nanocellulose: development and analysis of properties, Sci. Rep. 14 (2024) 23819, https://doi.org/10.1038/s41598-024-71619-5.

[112] H. Torabi, H. McGreal, H. Zarrin, E. Behzadfar, Effects of Rheological Properties on 3D Printing of Poly(lactic acid) (PLA) and Poly(hydroxy alkenoate) (PHA) Hybrid Materials, ACS Appl. Polym. Mater. 5 (2023) 4034–4044, https://doi.org/10.1021/acsapm.3c00271.

[113] M.R. Hasan, I.J. Davies, A. Pramanik, M. John, W.K. Biswas, Potential of recycled PLA in 3D printing: a review, Sustainable Manuf. Serv. Econ. 3 (2024) 100020, https://doi.org/10.1016/j.smse.2024.100020.

[114] V. DeStefano, S. Khan, A. Tabada, Applications of PLA in modern medicine, Eng. Regener. 1 (2020) 76–87, https://doi.org/10.1016/j.engreg.2020.08.002.

[115] L. Shao, Y.-C. Chang, C. Hao, M. Fei, B. Zhao, B.J. Bliss, J. Zhang, A chemical approach for the future of PLA upcycling: from plastic wastes to new 3D printing materials, Green Chem. 24 (2022) 8716–8724, https://doi.org/10.1039/d2gc01745h.

[116] M. Guicherd, M. Ben Khaled, M. Guéroult, J. Nomme, M. Dalibey, F. Grimaud, P. Alvarez, E. Kamionka, S. Gavalda, M. Noël, M. Vuillemin, E. Amillastre, D. Labourdette, G. Cioci, V. Tournier, V. Kitpreechavanich, P. Dubois, I. André, S. Duquesne, A. Marty, An engineered enzyme embedded into PLA to make self-biodegradable plastic, Nature 631 (2024) 884–890, https://doi.org/10.1038/s41586-024-07709-1.

[117] V.C. Agbakoba, N. Webb, E. Jegede, R. Phillips, S.P. Hlangothi, M.J. John, Mechanical Recycling of Waste PLA Generated from 3D Printing Activities: Filament Production and Thermomechanical Analysis, Macromol. Mater. Eng. 309 (2024) 2300276, https://doi.org/10.1002/mame.202300276.

[118] S. Bano, A.A. Aslam, A. Khan, A. Shabbir, F. Qayyum, N. Wahab, A. Jabar, I. Ul Islam, S.L. Ng, A mini-review on polyhydroxyalkanoates: Synthesis, extraction, characterization, and applications, Process Biochemistry 146 (2024) 250–261. doi:10.1016/j.procbio.2024.07.033.

[119] J. Chen, C. Gong, Preparation of polyhydroxyalkanoate nanocomposites for biomedical applications, Polym. Int. 74 (2025) 405–414, https://doi.org/10.1002/pi.6742.

[120] E. Marcello, R. Nigmatullin, P. Basnett, M. Maqbool, M.A. Prieto, J.C. Knowles, A. R. Boccaccini, I. Roy, 3D Melt-Extrusion Printing of Medium Chain Length Polyhydroxyalkanoates and their Application as Antibiotic-Free Antibacterial Scaffolds for Bone Regeneration, ACS Biomater Sci. Eng. 10 (2024) 5136–5153, https://doi.org/10.1021/acsbiomaterials.4c00624.

[121] T. Omura, N. Isobe, T. Miura, S. Ishii, M. Mori, Y. Ishitani, S. Kimura, K. Hidaka, K. Komiyama, M. Suzuki, K. Kasuya, H. Nomaki, R. Nakajima, M. Tsuchiya, S. Kawagucci, H. Mori, A. Nakayama, M. Kunioka, K. Kamino, T. Iwata, Microbial decomposition of biodegradable plastics on the deep-sea floor, Nat. Commun. 15 (2024) 568, https://doi.org/10.1038/s41467-023-44368-8.

[122] W. Zhou, S. Bergsma, D.I. Colpa, G.-J.-W. Euverink, J. Krooneman, Polyhydroxyalkanoates (PHAs) synthesis and degradation by microbes and applications towards a circular economy, J. Environ. Manage. 341 (2023) 118033, https://doi.org/10.1016/j.jenvman.2023.118033.

[123] M. Mehrpouya, H. Vahabi, M. Barletta, P. Laheurte, V. Langlois, Additive manufacturing of polyhydroxyalkanoates (PHAs) biopolymers: Materials, printing techniques, and applications, Mater. Sci. Eng. C 127 (2021) 112216, https://doi.org/10.1016/j.msec.2021.112216.

[124] M. Petousis, C. David, D. Sagris, N.K. Nasikas, V. Papadakis, A. Argyros, V. Stratiotou Efstratiadis, A. Gaganatsiou, N. Michailidis, N. Vidakis, Reinforced PHA/CNC Biocomposites in Extrusion-based Additive Manufacturing, ACS Omega 10 (2025) 36613–36630, https://doi.org/10.1021/acsomega.5c05743.

[125] L. Yu, F. Wang, S. Huang, Fabrication and Properties of Polycaprolactone/Poly (Butylene Succinate) Blends based on Electrospinning, Int J Polym Sci 2023 (2023) 1–12, https://doi.org/10.1155/2023/9471371.

[126] G.Ö. Kayan, A. Kayan, Polycaprolactone Composites/Blends and their applications especially in Water Treatment, ChemEngineering 7 (2023) 104, https://doi.org/10.3390/chemengineering7060104.

[127] M. Abedalwafa, F. Wang, L. Wang, C. Li, Biodegradable poly-epsilon-caprolactone (PCL) for tissue engineering applications: a review, Rev. Adv. Mater. Sci. 34 (2013) 123–140.

[128] D.S. Rosa, C.G.F. Guedes, F. Casarin, F.C. Bragança, The effect of the Mw of PEG in PCL/CA blends, Polym. Test. 24 (2005) 542–548, https://doi.org/10.1016/j.polymertesting.2005.02.002.

[129] Š. Krobot, V. Melčová, P. Menčík, S. Kontárová, M. Rampichová, V. Hedvičáková, E. Mojžišová, A. Baco, R. Přikryl, Poly(3-hydroxybutyrate) (PHB) and Polycaprolactone (PCL) based Blends for Tissue Engineering and Bone Medical applications Processed by FDM 3D Printing, Polymers (basel) 15 (2023) 2404, https://doi.org/10.3390/polym15102404.

[130] H. Liu, C. Li, S. Chen, P. Chen, J. Li, H. Jian, G. Guo, X. Chen, X. Zhu, J. Wu, Fabrication of 3D Printed Polylactic Acid/Polycaprolactone Nanocomposites with favorable Thermo-Responsive Cyclic Shape memory Effects, and Crystallization and Mechanical Properties, Polymers (basel) 15 (2023) 1533, https://doi.org/10.3390/polym15061533.

[131] C. Yue, M. Li, Y. Liu, Y. Fang, Y. Song, M. Xu, J. Li, Three-dimensional printing of cellulose nanofibers reinforced PHB/PCL/Fe3O4 magneto-responsive shape memory polymer composites with excellent mechanical properties, Addit. Manuf. 46 (2021) 102146, https://doi.org/10.1016/j.addma.2021.102146.

[132] M.A. Ntrivala, A.C. Pitsavas, K. Lazaridou, Z. Baziakou, D. Karavasili, M. Papadimitriou, C. Ntagkopoulou, E. Balla, D.N. Bikiaris, Polycaprolactone (PCL): the biodegradable polyester shaping the future of materials – a review on synthesis, properties, biodegradation, applications and future perspectives, Eur. Polym. J. 234 (2025) 114033, https://doi.org/10.1016/j.eurpolymj.2025.114033.

[133] D. Rigotti, L. Fambri, A. Pegoretti, Polyvinyl alcohol reinforced with carbon nanotubes for fused deposition modeling, J. Reinf. Plast. Compos. 37 (2018) 716–727, https://doi.org/10.1177/0731684418761224.

[134] H. Pei, L. Yang, Y. Xiong, Y. Chen, S. Shi, J. Jing, Fabrication, characterisation and properties of polyvinyl alcohol/graphene nanocomposite for fused filament fabrication processing, Plast., Rubber Compos. 50 (2021) 263–275, https://doi.org/10.1080/14658011.2020.1868668.

[135] A. Cataldi, D. Rigotti, V.D.H. Nguyen, A. Pegoretti, Polyvinyl alcohol reinforced with crystalline nanocellulose for 3D printing application, Mater. Today Commun. 15 (2018) 236–244, https://doi.org/10.1016/j.mtcomm.2018.02.007.

[136] G. Chen, N. Chen, Q. Wang, Preparation of poly (vinyl alcohol)/ionic liquid composites with improved processability and electrical conductivity for fused deposition modeling, Mater. Des. 157 (2018) 273–283, https://doi.org/10.1016/j.matdes.2018.07.054.

[137] R. Tylingo, P. Kempa, A. Banach-Kopeć, S. Mania, A novel method of creating thermoplastic chitosan blends to produce cell scaffolds by FDM additive manufacturing, Carbohydr. Polym. 280 (2022) 119028, https://doi.org/10.1016/j.carbpol.2021.119028.

[138] T.A. Tut, S. Cesur, E. Ilhan, A. Sahin, O.S. Yildirim, O. Gunduz, Gentamicin-loaded polyvinyl alcohol/whey protein isolate/hydroxyapatite 3D composite scaffolds with drug delivery capability for bone tissue engineering applications, Eur. Polym. J. 179 (2022) 111580, https://doi.org/10.1016/j.eurpolymj.2022.111580.

[139] G. Matijašić, M. Gretić, J. Vinčić, A. Poropat, L. Cuculić, T. Rahelić, Design and 3D printing of multi-compartmental PVA capsules for drug delivery, J Drug Deliv Sci Technol 52 (2019) 677–686, https://doi.org/10.1016/j.jddst.2019.05.037.

[140] H. Kim, G.H. Yang, C.H. Choi, Y.S. Cho, G. Kim, Gelatin/PVA scaffolds fabricated using a 3D-printing process employed with a low-temperature plate for hard tissue regeneration: Fabrication and characterizations, Int. J. Biol. Macromol. 120 (2018) 119–127, https://doi.org/10.1016/j.ijbiomac.2018.07.159.

[141] H. Windolf, R. Chamberlain, J. Quodbach, Dose-independent drug release from 3D printed oral medicines for patient-specific dosing to improve therapy safety, Int. J. Pharm. 616 (2022) 121555, https://doi.org/10.1016/j.ijpharm.2022.121555.

[142] S. Wang, L. Zhang, Z. Wang, Z. Song, H. Liu, Z. Tian, X. Xu, Humidity-adaptive, mechanically robust, and recyclable bioplastic films amplified by nanoconfined assembly, Aggregate 5 (2024) e643.

[143] Mohd. Kashif A, M.P. Dhavale, S.A. Shakib, A.S. Chavan, S.J. Pathan, Design and Development of 3D Printer Filament Maker Machine, International Journal of All Research Education & Scientific Methods 12 (2024) 1689–1696. doi:10.56025/IJARESM.2024.1207241689.

[144] L. Bhanuprakash, H. Kumar, A Review of Thermoplastic Filament Extruder Design and Fabrication Technologies, J. Phys. Conf. Ser. 2837 (2024) 012083, https://doi.org/10.1088/1742-6596/2837/1/012083.

[145] A. Denine, P. Siegfried, The assessment of the filament extruder equipment for 3D printing method, Journal of Social and Technological, Development 4 (2022) 32–38, https://doi.org/10.7251/STED2201032D.

[146] T. Hachimi, N. Naboulsi, F. Majid, R. Rhanim, I. Mrani, H. Rhanim, Design and Manufacturing of a 3D printer filaments extruder, Procedia Struct. Integrity 33 (2021) 907–916, https://doi.org/10.1016/j.prostr.2021.10.101.

[147] V. Mishra, S. Negi, S. Kar, A.K. Sharma, Y.N.K. Rajbahadur, A. Kumar, Recent advances in fused deposition modeling based additive manufacturing of thermoplastic composite structures: a review, J. Thermoplast. Compos. Mater. 36 (2023) 3094–3132, https://doi.org/10.1177/08927057221102857.

[148] V.K. Bokam, S.Y. Sonaye, P. Nagaraju, H.P.S. Naganaboyina, P. Sikder, Extrusion of uniform-diameter polyetheretherketone–magnesium phosphate bio-composite filaments for 3D printing of design-specific multi-functional implants, Mater. Adv. 4 (2023) 2926–2939, https://doi.org/10.1039/D3MA00172E.

[149] G. Barreto, S. Restrepo, C.M. Vieira, S.N. Monteiro, H.A. Colorado, Rice Husk with PLA: 3D Filament making and Additive Manufacturing of Samples for potential Structural applications, Polymers (basel) 16 (2024) 245, https://doi.org/10.3390/polym16020245.

[150] E. Pulidori, S. Micalizzi, E. Bramanti, L. Bernazzani, C. De Maria, C. Pelosi, M. R. Tinè, G. Vozzi, C. Duce, Valorization of not soluble byproducts deriving from green keratin extraction from poultry feathers as filler for biocomposites, J. Therm. Anal. Calorim. 147 (2022) 5377–5390, https://doi.org/10.1007/s10973-021-11166-7.

[151] C. Sciancalepore, E. Togliatti, M. Marozzi, F.M.A. Rizzi, D. Pugliese, A. Cavazza, O. Pitirollo, M. Grimaldi, D. Milanese, Flexible PBAT-Based Composite Filaments for Tunable FDM 3D Printing, ACS Appl. Bio Mater. 5 (2022) 3219–3229, https://doi.org/10.1021/acsabm.2c00203.

[152] S. Kumar, N. Chatterjee, S.K. Misra, Suitably Incorporated Hydrophobic, Redox-active Drug in Poly Lactic Acid-Graphene Nanoplatelet Composite Generates 3D-printed Medicinal Patch for Electrostimulatory Therapeutics, Langmuir 40 (2024) 11858–11872, https://doi.org/10.1021/acs.langmuir.3c03338.

[153] B. Ghezzi, B. Matera, M. Meglioli, F. Rossi, D. Duraccio, M.G. Faga, A. Zappettini, G.M. Macaluso, S. Lumetti, Composite PCL Scaffold with 70% β-TCP as Suitable Structure for Bone Replacement, Int. Dent. J. 74 (2024) 1220–1232, https://doi.org/10.1016/j.identj.2024.02.013.

[154] I. Galarreta-Rodriguez, A. Lopez-Ortega, E. Garayo, J.J. Beato-López, P. La Roca, V. Sanchez-Alarcos, V. Recarte, C. Gómez-Polo, J.I. Pérez-Landazábal, Magnetically activated 3D printable polylactic acid/polycaprolactone/magnetite composites for magnetic induction heating generation, Adv. Compos. Hybrid Mater. 6 (2023) 102, https://doi.org/10.1007/s42114-023-00687-4.

[155] K.K. Sonigara, J.V. Vaghasiya, C.C. Mayorga-Martinez, M. Pumera, Point-of-use upcycling of 3D printing waste for developing 3D-printed Zn–I 2 batteries, J Mater Chem A Mater 13 (2025) 11804–11816, https://doi.org/10.1039/D5TA00919G.

[156] D. Fico, D. Rizzo, V. De Carolis, C. Esposito Corcione, Bio-Composite Filaments based on Poly(Lactic Acid) and Cocoa Bean Shell Waste for Fused Filament Fabrication (FFF): production, Characterization and 3D Printing, Materials 17 (2024) 1260, https://doi.org/10.3390/ma17061260.

[157] S.A.S. Zaidi, C.E. Kwan, D. Mohan, S. Harun, A.A.I. Luthfi, M.S. Sajab, Evaluating the Stability of PLA-Lignin Filament Produced by Bench-Top Extruder for Sustainable 3D Printing, Materials 16 (2023) 1793, https://doi.org/10.3390/ma16051793.

[158] D. Fico, D. Rizzo, V. De Carolis, F. Montagna, C., Esposito Corcione, Sustainable Polymer Composites Manufacturing through 3D Printing Technologies by using Recycled Polymer and Filler, Polymers (basel) 14 (2022) 3756, https://doi.org/10.3390/polym14183756.

[159] M.A.F. Hanipa, S.A.S. Zaidi, M.S. Sajab, P.M. Abdul, K. Jamil, Comparative study of blending techniques in polylactic acid/cellulose nanofibrils green composites for benchtop 3D printing filaments, Polym. Compos. 46 (2025) 3070–3083, https://doi.org/10.1002/pc.29154.

[160] F. Wang, E.B. Tankus, F. Santarella, N. Rohr, N. Sharma, S. Märtin, M. Michalscheck, M. Maintz, S. Cao, F.M. Thieringer, Fabrication and Characterization of PCL/HA Filament as a 3D Printing Material using thermal Extrusion Technology for Bone Tissue Engineering, Polymers (basel) 14 (2022) 669, https://doi.org/10.3390/polym14040669.

[161] A. Spirio, R. Arrigo, A. Frache, L. Tuccinardi, R. Tuffi, Plastic waste recycling in additive manufacturing: Recovery of polypropylene from WEEE for the production of 3D printing filaments, J. Environ. Chem. Eng. 12 (2024) 112474, https://doi.org/10.1016/j.jece.2024.112474.

[162] 3devo, 100% recycled PET bottles - material report, 2020. https://support.3devo.com/hubfs/Knowledge%20Base%20Import/Recycled-PET-Material-Report.pdf (accessed November 30, 2025).

[163] N. Michailidis, M. Petousis, A. Maniadi, V. Papadakis, N. Mountakis, A. Argyros, N.K. Nasikas, E. Stratakis, N. Vidakis, Printability and thermomechanical metrics of high-density polyethylene doped with nano antimony TiN oxide, European Journal of Materials 5 (2025) 2463330, https://doi.org/10.1080/26889277.2025.2463330.

[164] M. Salignon, S. Gray, T. Rose, A. Encinas-Oropesa, A New Preparation Method for 3D Bio-composite Filament Manufacturing: a Study on the Effects of Ball Milling on the Cohesion/Adhesion of an Agave tequilana Bagasse/PLA Pellet Mixture, Circular Economy and Sustainability 3 (2023) 1441–1459, https://doi.org/10.1007/s43615-022-00241-2.

[165] V. Mishra, C.K. Ror, S. Negi, S. Kar, L.N. Borah, Development of sustainable 3D printing filaments using recycled/virgin ABS blends: Processing and characterization, Polym. Eng. Sci. 63 (2023) 1890–1899, https://doi.org/10.1002/pen.26330.

[166] A. Vinod, J. Tengsuthiwat, R. Vijay, M.R. Sanjay, S. Siengchin, Advancing additive manufacturing: 3D -printing of hybrid natural fiber sandwich (Nona/Soy-PLA) composites through filament extrusion and its effect on thermomechanical properties, Polym. Compos. 45 (2024) 7767–7789, https://doi.org/10.1002/pc.28302.

[167] E.M. Palmero, D. Casaleiz, J. De Vicente, J. Hernández-Vicen, S. López-Vidal, E. Ramiro, A. Bollero, Composites based on metallic particles and tuned filling factor for 3D-printing by Fused Deposition Modeling, Compos. Part A Appl. Sci. Manuf. 124 (2019) 105497, https://doi.org/10.1016/j.compositesa.2019.105497.

[168] R. Eickhoff, D. Nötzel, G. Oral, M. Scholz, T. Hanemann, Ceramic fused filament fabrication (CF3) of zirconia implants by using flexible, partially water-soluble binder systems, Mater. Des. 254 (2025) 114148, https://doi.org/10.1016/j.matdes.2025.114148.

[169] D. Arslan, M. Mihai, D. Therriault, M. Lévesque, Formulation and characterization of polyetherimide composites reinforced with recycled carbon fibers and thermal black particles for fused filament fabrication, Compos. Part A Appl. Sci. Manuf. 194 (2025) 108946, https://doi.org/10.1016/j.compositesa.2025.108946.

[170] P. Ghabezi, O. Sam-Daliri, T. Flanagan, M. Walls, N.M. Harrison, Upcycling waste polypropylene with basalt fibre reinforcement enhancing additive manufacturing feedstock for advanced mechanical performance, Appl. Mater. Today 41 (2024) 102486, https://doi.org/10.1016/j.apmt.2024.102486.

[171] V. Gaikwad, A. Ghose, S. Cholake, A. Rawal, M. Iwato, V. Sahajwalla, Transformation of E-Waste Plastics into Sustainable Filaments for 3D Printing, ACS Sustain. Chem. Eng. 6 (2018) 14432–14440, https://doi.org/10.1021/acssuschemeng.8b03105.

[172] D. Kodali, C.O. Umerah, M.O. Idrees, S. Jeelani, V.K. Rangari, Fabrication and characterization of polycarbonate-silica filaments for 3D printing applications, J. Compos. Mater. 55 (2021) 4575–4584, https://doi.org/10.1177/00219983211044748.

[173] I.L. Liakos, A. Mondini, E. Del Dottore, C. Filippeschi, F. Pignatelli, B. Mazzolai, 3D printed composites from heat extruded polycaprolactone/sodium alginate filaments and their heavy metal adsorption properties, Mater. Chem. Front. 4 (2020) 2472–2483, https://doi.org/10.1039/D0QM00159G.

[174] D.L.O. Ramos, R.D. Crapnell, R. Asra, E. Bernalte, A.C.M. Oliveira, R.A.A. Muñoz, E.M. Richter, A.M. Jones, C.E. Banks, Conductive Polypropylene Additive Manufacturing Feedstock: Application to Aqueous Electroanalysis and Unlocking Nonaqueous Electrochemistry and Electrosynthesis, ACS Appl. Mater. Interfaces 16 (2024) 56006–56018, https://doi.org/10.1021/acsami.4c12967.

[175] A. Enchinton, A.C. Martinez, K.R. Gonzalez, C.A. Fernandez, S. Balivada, L.C. Merrill, J.A. Cardenas, S. Panier, A. Maurel, 3D Printing of Highly Porous Polypropylene Separators for Lithium-Ion Batteries Using Fused Deposition Modeling and Thermally Induced Phase Separation, Adv Mater Technol n/a (2025) e00912. doi:10.1002/admt.202500912.

[176] M. Khamvongsa, K. Milton, T.R. Faisal, Mechanical characterization of low-cost 3D FDM printed scaffolds fabricated with synthesized PLA/HA bio-composite filament, Annals of 3D Printed Medicine 18 (2025) 100194, https://doi.org/10.1016/j.stlm.2025.100194.

[177] M. Martiček, R. Tauberová, J. Kaščak, R. Vandžura, E. Sukić, L. Knapčíková, The Influence of selected Parameters of Recycled polyvinyl Butyral on the Sustainable Filament Extrusion Process, Appl. Sci. 14 (2024) 9752, https://doi.org/10.3390/app14219752.

[178] M. Tahir, A. Rahimizadeh, J. Kalman, K. Fayazbakhsh, L. Lessard, Experimental and analytical investigation of 3D printed specimens reinforced by different forms of recyclates from wind turbine waste, Polym. Compos. 42 (2021) 4533–4548, https://doi.org/10.1002/pc.26166.

[179] F. Zaccardi, E. Toto, M.G. Santonicola, S. Laurenzi, 3D printing of radiation shielding polyethylene composites filled with Martian regolith simulant using fused filament fabrication, Acta Astronaut. 190 (2022) 1–13, https://doi.org/10.1016/j.actaastro.2021.09.040.

[180] A.J.B. Campuzano, R.B. Rezende, N.C. Taborda, J.C. dos Santos, F.V. Pereira, T. H. Panzera, Physical and mechanical properties of fused deposition modelling PLA/carbon dot nanocomposites, Mater. Today Commun. 40 (2024) 110025, https://doi.org/10.1016/j.mtcomm.2024.110025.

[181] G. Asai, C. Jansari, F. Lachaud, K. Masania, J. Morlier, Ecodesign of 3D volumetric fiber-composite structures with topology optimization, Compos. Part A Appl. Sci. Manuf. 190 (2025) 108615, https://doi.org/10.1016/j.compositesa.2024.108615.

[182] C. Cardona, A.H. Curdes, A.J. Isaacs, Effects of Filament Diameter Tolerances in Fused Filament Fabrication, IU Journal of Undergraduate Research 2 (2016) 44–47, https://doi.org/10.14434/iujur.v2i1.20917.

[183] N.A.S. Mohd Pu'ad, R.H. Abdul Haq, H. Mohd Noh, H.Z. Abdullah, M.I. Idris, T.C. Lee, Review on the fabrication of fused deposition modelling (FDM) composite filament for biomedical applications, Mater Today Proc 29 (2020) 228–232. doi: 10.1016/j.matpr.2020.05.535.

[184] Print your city project, (2025). https://www.printyour.city (accessed November 11, 2025).

[185] Oceana Plastic Project, (2025). https://www.solariscommunity.com/oceana (accessed November 11, 2025).

[186] vanPlestik, (2025). https://vanplestik.nl/en/about-vanplestik/ (accessed November 11, 2025).

[187] Aectual, (2025). https://www.aectual.com/about (accessed November 11, 2025).

[188] F. Raspall, C. Bañón, Large-Scale 3D Printing Using Recycled PET. The Case of Upcycle Lab @ DB Schenker Singapore, in: Yuan Philip F., H. Chai, C. Yan, K. Li, T. Sun (Eds.), Hybrid Intelligence, Springer Nature Singapore, Singapore, 2023: pp. 432–442.

[189] THE CAB – THE FIRST 3D-PRINTED RV MADE FROM RECYCLED POLYMER, (2025). https://caracol-am.com/resources/case-studies/the-cab-the-first-3d-printed-rv-shell-made-from-recycled-polymer (accessed November 11, 2025).

[190] D.J. Byard, A.L. Woern, R.B. Oakley, M.J. Fiedler, S.L. Snabes, J.M. Pearce, Green fab lab applications of large-area waste polymer-based additive manufacturing, Addit. Manuf. 27 (2019) 515–525, https://doi.org/10.1016/j.addma.2019.03.006.

[191] P. Dai, Z. Luo, Y. Wang, J. Mbabazi, S. Liu, H. Ren, M. Zong, L. Yang, J. Lu, P. Zhu, Q. Lyu, Waste plastic fiber reinforced cementitious cavity structures manufactured by mortar extrusion 3D printing, Constr. Build. Mater. 487 (2025) 142127, https://doi.org/10.1016/j.conbuildmat.2025.142127.

[192] M.K. Singh, A.K. Mohanty, M. Misra, Upcycling of waste polyolefins in natural fiber and sustainable filler-based biocomposites: a study on recent developments and future perspectives, Compos. B Eng. 263 (2023) 110852, https://doi.org/10.1016/j.compositesb.2023.110852.

[193] C. Suescun Gonzalez, F.A. Cruz Sanchez, H. Boudaoud, C. Nouvel, J.M. Pearce, Multi-material distributed recycling via material extrusion: recycled high density polyethylene and poly (ethylene terephthalate) mixture, Polym. Eng. Sci. 64 (2024) 1555–1570, https://doi.org/10.1002/pen.26643.

[194] B. Maldonado-García, A.K. Pal, M. Misra, S. Gregori, A.K. Mohanty, Sustainable 3D printed composites from recycled ocean plastics and pyrolyzed soy-hulls: Optimization of printing parameters, performance studies and prototypes development, Composites, Part C: Open Access 6 (2021) 100197, https://doi.org/10.1016/j.jcomc.2021.100197.

[195] PlasticTinkers, (2025). https://www.plastictinkers.com (accessed November 11, 2025).

[196] cults3d.com, (2025). https://cults3d.com/en/collections/best-stl-files-upcycle-3d-printing?srsltid=AfmBOoqQXwcmuCS1swQSKvHiOE0kkyT4QOFsDWWo3lLoHFf6MZkzm77o (accessed November 11, 2025).

[197] S. Kim, M.A. Rahman, M. Arifuzzaman, D.B. Gilmer, B. Li, J.K. Wilt, E. Lara-Curzio, T. Saito, Closed-loop additive manufacturing of upcycled commodity plastic through dynamic cross-linking, Sci Adv 8 (2022) eabn6006, https://doi.org/10.1126/sciadv.abn6006.

[198] F.A. Cruz Sanchez, H. Boudaoud, M. Camargo, J.M. Pearce, Plastic recycling in additive manufacturing: a systematic literature review and opportunities for the circular economy, J Clean Prod 264 (2020) 121602, https://doi.org/10.1016/j.jclepro.2020.121602.

[199] A. Romani, L. Perusin, M. Ciurnelli, M. Levi, Characterization of PLA feedstock after multiple recycling processes for large-format material extrusion additive manufacturing, Mater. Today Sustainability 25 (2024) 100636, https://doi.org/10.1016/j.mtsust.2023.100636.

[200] X. Wei, R. Bähr, A comparative study of 3D printing with virgin and recycled polylactic acid filaments, CIRP J. Manuf. Sci. Technol. 54 (2024) 75–84, https://doi.org/10.1016/j.cirpj.2024.08.007.

[201] J. Su, N. Wei Long, A. Jia, Y. Wai Yee, C. Chee Kai, S.L. Sing, Achieving sustainability by additive manufacturing: a state-of-the-art review and perspectives, Virtual Phys Prototyp 19 (2024) e2438899, https://doi.org/10.1080/17452759.2024.2438899.

[202] A. Yousaf, A. Al Rashid, R. Polat, M. Koç, Potential and challenges of recycled polymer plastics and natural waste materials for additive manufacturing, Sustain. Mater. Technol. 41 (2024) e01103, https://doi.org/10.1016/j.susmat.2024.e01103.

[203] B. Wang, A. Pierre-Antoine, M. Guillaume, G. Yang, S. Zhou, Sustainable additive manufacturing: Microstructural evolution and mechanical viability of recycled Flax/PP via fused granular fabrication, Ind. Crops Prod. 236 (2025) 121997, https://doi.org/10.1016/j.indcrop.2025.121997.

[204] R. Djonyabe Habiba, C. Malça, R. Branco, Exploring the potential of Recycled Polymers for 3D Printing applications, A Review, Materials 17 (2024), https://doi.org/10.3390/ma17122915.

[205] J. Hopewell, R. Dvorak, E. Kosior, Plastics recycling: challenges and opportunities, Philos. Trans. R. Soc., B 364 (2009) 2115–2126, https://doi.org/10.1098/rstb.2008.0311.

[206] W. Yang, W. Chang, J. Zhang, G.H. Yeoh, C. Boyer, C.H. Wang, Effects of waste coffee grounds on the mechanical properties, flame retardancy and toxic gas production of epoxy composites, Mater. Des. 224 (2022) 111347, https://doi.org/10.1016/j.matdes.2022.111347.

[207] M.A. Morales, A. Maranon, C. Hernandez, A. Porras, Development and Characterization of a 3D Printed Cocoa Bean Shell Filled Recycled Polypropylene for Sustainable Composites, Polymers (basel) 13 (2021) 3162, https://doi.org/10.3390/polym13183162.

[208] D. Stoof, K. Pickering, Sustainable composite fused deposition modelling filament using recycled pre-consumer polypropylene, Compos. B Eng. 135 (2018) 110–118, https://doi.org/10.1016/j.compositesb.2017.10.005.

[209] S. Balou, I. Ahmed, A. Priye, From Waste to Filament: Development of Biomass-Derived Activated Carbon-Reinforced PETG Composites for Sustainable 3D Printing, ACS Sustain. Chem. Eng. 11 (2023) 12667–12676, https://doi.org/10.1021/acssuschemeng.3c02685.

[210] H. Long, L. Hu, F. Yang, Q. Cai, Z. Zhong, S. Zhang, L. Guan, D. Xiao, W. Zheng, W. Zhou, Y. Wei, K. Frank, X. Dong, Enhancing the performance of polylactic acid composites through self-assembly lignin nanospheres for fused deposition modeling, Compos. B Eng. 239 (2022) 109968, https://doi.org/10.1016/j.compositesb.2022.109968.

[211] L. Aliotta, C. Sergi, B.D. Pont, M.-B. Coltelli, V. Gigante, A. Lazzeri, Sustainable 3D printed poly (lactic acid) (PLA)/Hazelnut shell powder bio composites for design applications, Mater. Today Sustainability 26 (2024) 100780, https://doi.org/10.1016/j.mtsust.2024.100780.

[212] D.V. Lohar, A.M. Nikalje, P.G. Damle, Synthesis and characterization of PLA hybrid composites using bio waste fillers, Mater. Today Proc. 72 (2023) 2155–2162, https://doi.org/10.1016/j.matpr.2022.08.276.

[213] F. Yang, X. Ye, J. Zhong, Z. Lin, S. Wu, Y. Hu, W. Zheng, W. Zhou, Y. Wei, X. Dong, Recycling of waste crab shells into reinforced poly (lactic acid) biocomposites for 3D printing, Int. J. Biol. Macromol. 234 (2023) 122974, https://doi.org/10.1016/j.ijbiomac.2022.12.193.

[214] Y. Sun, D. Lee, Y. Wang, S. Li, J. Ying, X. Liu, G. Xu, J. Gwon, Q. Wu, Effect of infill value on decay resistance, thermal, and mechanical properties of 3D printed polylactic acid composites filled with wood fibers, BioResources 15 (2020) 6724–6734, https://doi.org/10.15376/biores.15.3.6724-6734.

[215] S.R. Begum, B.A. Devan, S. Kavya, H. Pranav, R. Rakul, M. Vasumathi, P. Senthamaraikannan, A.A. Adediran, M. Saravana Kumar, Study on pistachio shell filled PLA composites for FDM-based processing, Sci. Rep. 15 (2025) 38215, https://doi.org/10.1038/s41598-025-22006-1.

[216] A. Haryńska, H. Janik, M. Sienkiewicz, B. Mikolaszek, J. Kucińska-Lipka, PLA–Potato Thermoplastic Starch Filament as a Sustainable Alternative to the conventional PLA Filament: Processing, Characterization, and FFF 3D Printing, ACS Sustain. Chem. Eng. 9 (2021) 6923–6938, https://doi.org/10.1021/acssuschemeng.0c09413.

[217] M.A. Kacem, R. Bibb, F. Scarpa, M. Bodaghi, Sustainable PLA- and bio-epoxy-based bio-composites reinforced with sea urchin residues: from waste to worth, Results Eng. 28 (2025) 108137, https://doi.org/10.1016/j.rineng.2025.108137.

[218] I. Beşliu-Băncescu, I. Tamaşag, Heat Treatment effect on some Mechanical Properties of FDM-Manufactured PCL Wood-Based Biopolymer, Adv. Polym. Tech. 2024 (2024) 7432507, https://doi.org/10.1155/2024/7432507.

[219] T.N. Tran, I.S. Bayer, J.A. Heredia-Guerrero, M. Frugone, M. Lagomarsino, F. Maggio, A. Athanassiou, Cocoa Shell Waste Biofilaments for 3D Printing applications, Macromol. Mater. Eng. 302 (2017) 1700219, https://doi.org/10.1002/mame.201700219.

[220] A. Sanz de León, J.A. Pulido, N. Fernández-Delgado, F.J. Delgado, S.I. Molina, Chitin Nanocomposites for Fused Filament Fabrication: Flexible Materials with Enhanced Interlayer Adhesion, ACS Appl. Mater. Interfaces 16 (2024) 35554–35565, https://doi.org/10.1021/acsami.4c06358.

[221] A.N.M.A. Haque, M. Naebe, D. Mielewski, A. Kiziltas, Waste wool/polycaprolactone filament towards sustainable use in 3D printing, J. Clean. Prod. 386 (2023) 135781, https://doi.org/10.1016/j.jclepro.2022.135781.

[222] O. Ohaeri, D. Cree, Development and Characterization of PHB-PLA/Corncob Composite for Fused Filament Fabrication, Journal of Composites Science 6 (2022) 249, https://doi.org/10.3390/jcs6090249.

[223] A. Romani, M. Paramatti, L. Gallo, M. Levi, Large-format material extrusion additive manufacturing of PLA, LDPE, and HDPE compound feedstock with spent coffee grounds, Int. J. Adv. Manuf. Technol. 134 (2024) 1845–1861, https://doi.org/10.1007/s00170-024-14214-2.

[224] E. Jo, K. Copenhaver, H. Tekinalp, T. Smith, H. Wang, U. Vaidya, S. Ozcan, S. Kim, Effect of toolpath in large-format additive manufacturing with bio-derived composites, Virtual Phys Prototyp 20 (2025) e2503257, https://doi.org/10.1080/17452759.2025.2503257.

[225] X. Zhao, E. Webb, N. Boggess, K. McCracken, E. Carter, O. Oyedeji, A. Roschli, T. Smith, S. Ozcan, J. Malmstead, M. Dickerson, A. Elliott, H. Tekinalp, Design and scale-up of 3D printed bat houses with biomass-derived polymer composites, Additive Manufacturing, Frontiers (2025) 200256, https://doi.org/10.1016/j.amf.2025.200256.

[226] P. Burgos Pintos, M. Maturi, A. de León, S.I. Molina, Development of Polymer Composites using Surface-Modified Olive pit Powder for Fused Granular Fabrication, Polymers (basel) 16 (2024), https://doi.org/10.3390/polym16212981.

[227] A.A. Zaky, J. Simal-Gandara, J.-B. Eun, J.-H. Shim, A.M. Abd El-Aty, Bioactivities, Applications, Safety, and Health Benefits of Bioactive Peptides From Food and By-

Products: A Review, Front Nutr Volume 8-2021 (2022). doi:10.3389/fnut.2021.815640.
[228] S. Ben-Othman, I. Jõudu, R. Bhat, Bioactives from Agri-Food Wastes: present Insights and Future challenges, Molecules 25 (2020) 510, https://doi.org/10.3390/molecules25030510.
[229] E. Bolat, S. Sarıtaş, H. Duman, F. Eker, E. Akdaşçi, S. Karav, A.M. Witkowska, Polyphenols: Secondary Metabolites with a Biological Impression, Nutrients 16 (2024) 2550, https://doi.org/10.3390/nu16152550.
[230] K. Purohit, N. Reddy, A. Sunna, Exploring the potential of Bioactive Peptides: from Natural sources to Therapeutics, Int. J. Mol. Sci. 25 (2024) 1391, https://doi.org/10.3390/ijms25031391.
[231] J. Park, J. Choi, D.-D. Kim, S. Lee, B. Lee, Y. Lee, S. Kim, S. Kwon, M. Noh, M.-O. Lee, Q.-V. Le, Y.-K. Oh, Bioactive Lipids and their Derivatives in Biomedical applications, Biomol Ther (seoul) 29 (2021) 465–482, https://doi.org/10.4062/biomolther.2021.107.
[232] M.C. Bergonzi, C.M. Heard, J. Garcia-Pardo, Bioactive Molecules from Plants: Discovery and Pharmaceutical applications, Pharmaceutics 14 (2022) 2116, https://doi.org/10.3390/pharmaceutics14102116.
[233] A. Roman-Benn, C.A. Contador, M.-W. Li, H.-M. Lam, K. Ah-Hen, P.E. Ulloa, M.C. Ravanal, Pectin: an overview of sources, extraction and applications in food products, biomedical, pharmaceutical and environmental issues, Food Chem. Adv. 2 (2023) 100192, https://doi.org/10.1016/j.focha.2023.100192.
[234] X. Shuai, J. Chen, Q. Liu, H. Dong, T. Dai, Z. Li, C. Liu, R. Wang, The Effects of Pectin Structure on Emulsifying, Rheological, and In Vitro Digestion Properties of Emulsion, Foods 11 (2022), https://doi.org/10.3390/foods11213444.
[235] B. Ozturk, J. Winterburn, M. Gonzalez-Miquel, Orange peel waste valorisation through limonene extraction using bio-based solvents, Biochem. Eng. J. 151 (2019) 107298, https://doi.org/10.1016/j.bej.2019.107298.
[236] F. Rodrigues, F.B. Pimentel, M.B.P.P. Oliveira, Olive by-products: Challenge application in cosmetic industry, Ind. Crops Prod. 70 (2015) 116–124, https://doi.org/10.1016/j.indcrop.2015.03.027.
[237] S.M. Ferreira, Z. Falé, L. Santos, Sustainability in Skin Care: Incorporation of Avocado Peel Extracts in Topical Formulations, Molecules 27 (2022), https://doi.org/10.3390/molecules27061782.
[238] M. Donner, Y. Erraach, F. López-i-Gelats, J. Manuel-i-Martin, T. Yatribi, I. Radić, F. El Hadad-Gauthier, Circular bioeconomy for olive oil waste and by-product valorisation: Actors' strategies and conditions in the Mediterranean area, J. Environ. Manage. 321 (2022) 115836, https://doi.org/10.1016/j.jenvman.2022.115836.
[239] T.A. Comunian, M.P. Silva, C.J.F. Souza, The use of food by-products as a novel for functional foods: their use as ingredients and for the encapsulation process, Trends Food Sci. Technol. 108 (2021) 269–280, https://doi.org/10.1016/j.tifs.2021.01.003.
[240] P.C. Nath, A. Ojha, S. Debnath, M. Sharma, P.K. Nayak, K. Sridhar, B.S. Inbaraj, Valorization of Food Waste as Animal Feed: a step towards Sustainable Food Waste Management and Circular Bioeconomy, Animals 13 (2023), https://doi.org/10.3390/ani13081366.
[241] M. Bartolomei, A.L. Capriotti, Y. Li, C. Bollati, J. Li, A. Cerrato, L. Cecchi, R. Pugliese, M. Bellumori, N. Mulinacci, A. Laganà, A. Arnoldi, C. Lammi, Exploitation of Olive (Olea europaea L.) seed Proteins as Upgraded source of Bioactive Peptides with Multifunctional Properties: Focus on Antioxidant and Dipeptidyl-Dipeptidase—IV Inhibitory Activities, and Glucagon-like Peptide 1 improved Modulation, Antioxidants 11 (2022), https://doi.org/10.3390/antiox11091730.
[242] A. Givonetti, S. Tonello, C. Cattaneo, D. D'Onghia, N. Vercellino, P.P. Sainaghi, D. Colangelo, M. Cavaletto, Hempseed Water-Soluble Protein Fraction and its Hydrolysate Display Different Biological Features, Life 15 (2025), https://doi.org/10.3390/life15020225.
[243] J. Li, C. Bollati, M. Bartolomei, A. Mazzolari, A. Arnoldi, G. Vistoli, C. Lammi, Hempseed (Cannabis sativa) Peptide H3 (IGFLIIWV) Exerts Cholesterol-Lowering Effects in Human Hepatic Cell Line, Nutrients 14 (2022), https://doi.org/10.3390/nu14091804.
[244] C. Lammi, C. Zanoni, A. Arnoldi, Three Peptides from Soy Glycinin Modulate Glucose Metabolism in Human Hepatic HepG2 Cells, Int. J. Mol. Sci. 16 (2015) 27362–27370, https://doi.org/10.3390/ijms161126029.
[245] C. Bollati, I. Cruz-Chamorro, G. Aiello, J. Li, M. Bartolomei, G. Santos-Sánchez, G. Ranaldi, S. Ferruzza, Y. Sambuy, A. Arnoldi, C. Lammi, Investigation of the intestinal trans-epithelial transport and antioxidant activity of two hempseed peptides WVSPLAGRT (H2) and IGFLIIWV (H3), Food Res. Int. 152 (2022) 110720, https://doi.org/10.1016/j.foodres.2021.110720.
[246] F. Tonolo, S. Coletta, F. Fiorese, A. Grinzato, M. Albanesi, A. Folda, S. Ferro, A. De Mario, I. Piazza, C. Mammucari, G. Arrigoni, O. Marin, G. Cestonaro, L. Nataloni, E. Costanzo, C. Lodovichi, M.P. Rigobello, M. de Bernard, Sunflower seed-derived bioactive peptides show antioxidant and anti-inflammatory activity: from in silico simulation to the animal model, Food Chem. 439 (2024) 138124, https://doi.org/10.1016/j.foodchem.2023.138124.
[247] L. d'Adduzio, M. Fanzaga, A.L. Capriotti, E. Taglioni, G. Boschin, A. Laganà, L. Rueller, J. Robert, A. van Gemmern, C. Bollati, C. Lammi, Ultrasonication coupled to enzymatic hydrolysis of soybean okara proteins for producing bioactive and bioavailable peptides, Curr. Res. Food Sci. 9 (2024) 100919, https://doi.org/10.1016/j.crfs.2024.100919.
[248] M. Saubenova, Y. Oleinikova, A. Rapoport, S. Maksimovich, Z. Yermekbay, E. Khamedova, Bioactive Peptides Derived from Whey Proteins for Health and Functional Beverages, Fermentation 10 (2024) 359, https://doi.org/10.3390/fermentation10070359.
[249] M. Bartolomei, J. Cropotova, C. Bollati, K. Kvangarsnes, L. d'Adduzio, J. Li, G. Boschin, C. Lammi, Rainbow Trout (Oncorhynchus mykiss) as source of Multifunctional Peptides with Antioxidant, ACE and DPP-IV Inhibitory Activities, Nutrients 15 (2023), https://doi.org/10.3390/nu15040829.
[250] M.G. Romero-Garay, E. Montalvo-González, C. Hernández-González, A. Soto-Domínguez, E.M. Becerra-Verdín, M., De Lourdes García-Magaña, Bioactivity of peptides obtained from poultry by-products: a review, Food Chem.: X 13 (2022) 100181, https://doi.org/10.1016/j.fochx.2021.100181.
[251] M. Tanaka, Y. Koyama, Y. Nomura, Effects of Collagen Peptide Ingestion on UV-B-Induced Skin damage, Biosci. Biotechnol. Biochem. 73 (2009) 930–932, https://doi.org/10.1271/bbb.80649.
[252] V. Zague, V. de Freitas, M. da C. Rosa, G.Á. de Castro, R.G. Jaeger, G.M. Machado-Santelli, Collagen Hydrolysate Intake Increases Skin Collagen Expression and Suppresses Matrix Metalloproteinase 2 Activity, J Med Food 14 (2011) 618–624. doi:10.1089/jmf.2010.0085.
[253] F. Apone, A. Barbulova, M.G. Colucci, Plant and Microalgae Derived Peptides are Advantageously Employed as Bioactive Compounds in cosmetics, Front. Plant Sci. 10–2019 (2019), https://doi.org/10.3389/fpls.2019.00756.
[254] S. Ghalamara, C. Brazinha, S. Silva, M. Pintado, Valorization of fish Processing by-Products: Biological and Functional Properties of Bioactive Peptides, Curr. Food Sci. Technol. Rep. 2 (2024) 393–409, https://doi.org/10.1007/s43555-024-00045-5.
[255] J. Azmir, I.S.M. Zaidul, M.M. Rahman, K.M. Sharif, A. Mohamed, F. Sahena, M.H. A. Jahurul, K. Ghafoor, N.A.N. Norulaini, A.K.M. Omar, Techniques for extraction of bioactive compounds from plant materials: a review, J. Food Eng. 117 (2013) 426–436, https://doi.org/10.1016/j.jfoodeng.2013.01.014.
[256] E. Quitério, C. Grosso, R. Ferraz, C. Delerue-Matos, C. Soares, A critical Comparison of the Advanced Extraction Techniques Applied to Obtain Health-Promoting Compounds from Seaweeds, Mar. Drugs 20 (2022), https://doi.org/10.3390/md20110677.
[257] R. Colombo, V. Pellicorio, M. Barberis, I. Frosi, A. Papetti, Recent advances in the valorization of seed wastes as source of bioactive peptides with multifunctional properties, Trends Food Sci. Technol. 144 (2024) 104322, https://doi.org/10.1016/j.tifs.2023.104322.
[258] Q. Aili, D. Cui, Y. Li, W. Zhige, W. Yongping, Y. Minfen, L. Dongbin, R. Xiao, W. Qiang, Composing functional food from agro-forest wastes: Selectively extracting bioactive compounds using supercritical fluid extraction, Food Chem. 455 (2024) 139848, https://doi.org/10.1016/j.foodchem.2024.139848.
[259] J.A. Almohasin, J. Balag, V.G. Miral, R.V. Moreno, L.J. Tongco, E.C.R. Lopez, Green Solvents for Liquid–Liquid Extraction: recent advances and Future Trends, Engineering Proceedings 56 (2023), https://doi.org/10.3390/ASEC2023-16278.
[260] E. Watt, M.A. Abdelwahab, A.K. Mohanty, M. Misra, Biocomposites from biobased polyamide 4,10 and waste corn cob based biocarbon, Compos. Part A Appl. Sci. Manuf. 145 (2021) 106340, https://doi.org/10.1016/j.compositesa.2021.106340.
[261] D.F. Williams, Biocompatibility pathways and mechanisms for bioactive materials: the bioactivity zone, Bioact. Mater. 10 (2022) 306–322, https://doi.org/10.1016/j.bioactmat.2021.08.014.
[262] P. Govindaraj, N. Alungal, Kannan, S, Silver Conjugated Nickel Oxide Nanoparticle Dependent Microfluid Non-Enzymatic Colorimetric Paper-Based Biosensor for Uric Acid Detection, Biochem Eng J 215 (2025) 109622, https://doi.org/10.1016/j.bej.2024.109622.
[263] F. Cestari, M. Petretta, Y. Yang, A. Motta, B. Grigolo, V.M. Sglavo, 3D printing of PCL/nano-hydroxyapatite scaffolds derived from biogenic sources for bone tissue engineering, Sustain. Mater. Technol. 29 (2021) e00318, https://doi.org/10.1016/j.susmat.2021.e00318.
[264] F. Yang, J. Zeng, H. Long, J. Xiao, Y. Luo, J. Gu, W. Zhou, Y. Wei, X. Dong, Micrometer Copper-Zinc Alloy Particles-Reinforced Wood Plastic Composites with High Gloss and Antibacterial Properties for 3D Printing, Polymers (basel) 12 (2020) 621, https://doi.org/10.3390/polym12030621.
[265] A. Bastas, Sustainable Manufacturing Technologies: a Systematic Review of latest Trends and Themes, Sustainability 13 (2021) 4271, https://doi.org/10.3390/su13084271.
[266] A. Dukle, M.R. Sankar, 3D-printed polylactic acid scaffolds for bone tissue engineering: Bioactivity enhancing strategies based on composite filaments and coatings, Mater. Today Commun. 40 (2024) 109776, https://doi.org/10.1016/j.mtcomm.2024.109776.
[267] A.-C. Mocanu, A.-E. Constantinescu, M.-A. Pandele, Ș.I. Voicu, R.-C. Ciocoiu, D. Batalu, A. Semenescu, F. Miculescu, L.-T. Ciocan, Biocompatible Composite Filaments Printable by Fused Deposition Modelling Technique: selection of Tuning Parameters by Influence of Biogenic Hydroxyapatite and Graphene Nanoplatelets Ratios, Biomimetics 9 (2024), https://doi.org/10.3390/biomimetics9030189.
[268] R.F. Richter, C. Vater, M. Korn, T. Ahlfeld, M. Rauner, W. Pradel, B. Stadlinger, M. Gelinsky, A. Lode, P. Korn, Treatment of critical bone defects using calcium phosphate cement and mesoporous bioactive glass providing spatiotemporal drug delivery, Bioact. Mater. 28 (2023) 402–419, https://doi.org/10.1016/j.bioactmat.2023.06.001.
[269] M. Lu, C. Zhou, C. Wang, R.B. Jackson, C.P. Kempes, Worldwide scaling of waste generation in urban systems, Nat. Cities 1 (2024) 126–135, https://doi.org/10.1038/s44284-023-00021-5.
[270] M.F. Cunha, G. Pellino, Environmental effects of surgical procedures and strategies for sustainable surgery, Nat. Rev. Gastroenterol. Hepatol. 20 (2023) 399–410, https://doi.org/10.1038/s41575-022-00716-5.
[271] G. Liu, B. Zhang, T. Wan, C. Zhou, Y. Fan, W. Tian, W. Jing, A 3D-printed biphasic calcium phosphate scaffold loaded with platelet lysate/gelatin methacrylate to

promote vascularization, J. Mater. Chem. B 10 (2022) 3138–3151, https://doi.org/10.1039/D2TB00006G.

[272] T. Distler, N. Fournier, A. Grünewald, C. Polley, H. Seitz, R. Detsch, A. R. Boccaccini, Polymer-Bioactive Glass Composite Filaments for 3D Scaffold Manufacturing by Fused Deposition Modeling: Fabrication and Characterization, Front. Bioeng. Biotechnol. 8–2020 (2020), https://doi.org/10.3389/fbioe.2020.00552.

[273] J. Domínguez-Robles, N.K. Martin, M.L. Fong, S.A. Stewart, N.J. Irwin, M.I. Rial-Hermida, R.F. Donnelly, E. Larrañeta, Antioxidant PLA Composites Containing Lignin for 3D Printing applications: a potential Material for Healthcare applications, Pharmaceutics 11 (2019), https://doi.org/10.3390/pharmaceutics11040165.

[274] G.F. Ferrazzano, I. Amato, A. Ingenito, A. Zarrelli, G. Pinto, A. Pollio, Plant Polyphenols and their Anti-Cariogenic Properties: a Review, Molecules 16 (2011) 1486–1507, https://doi.org/10.3390/molecules16021486.

[275] N. Li, S.B. Khan, S. Chen, W. Aiyiti, J. Zhou, B. Lu, Promising New Horizons in Medicine: Medical Advancements with Nanocomposite Manufacturing via 3D Printing, Polymers (basel) 15 (2023) 4122, https://doi.org/10.3390/polym15204122.

[276] P.S. Zieliński, P.K.R. Gudeti, T. Rikmanspoel, M.K. Włodarczyk-Biegun, 3D printing of bio-instructive materials: Toward directing the cell, Bioact. Mater. 19 (2023) 292–327, https://doi.org/10.1016/j.bioactmat.2022.04.008.

[277] A.J. Kyser, B. Fotouh, M.Y. Mahmoud, H.B. Frieboes, Rising role of 3D-printing in delivery of therapeutics for infectious disease, J. Control. Release 366 (2024) 349–365, https://doi.org/10.1016/j.jconrel.2023.12.051.

[278] S.V. Kallivokas, L.C. Kontaxis, S. Psarras, M. Roumpi, O. Ntousi, I. Kakkos, D. Deligianni, G.K. Matsopoulos, D.I. Fotiadis, V. Kostopoulos, A combined Computational and Experimental Analysis of PLA and PCL Hybrid Nanocomposites 3D Printed Scaffolds for Bone Regeneration, Biomedicines 12 (2024) 261, https://doi.org/10.3390/biomedicines12020261.

[279] M. Gharibshahian, M. Salehi, N. Beheshtizadeh, M. Kamalabadi-Farahani, A. Atashi, M.-S. Nourbakhsh, M. Alizadeh, Recent advances on 3D-printed PCL-based composite scaffolds for bone tissue engineering, Front. Bioeng. Biotechnol. 11 (2023) 1168504, https://doi.org/10.3389/fbioe.2023.1168504.

[280] T. Tracy, L. Wu, X. Liu, S. Cheng, X. Li, 3D printing: innovative solutions for patients and pharmaceutical industry, Int. J. Pharm. 631 (2023) 122480, https://doi.org/10.1016/j.ijpharm.2022.122480.

[281] S.I. Talabi, S.O. Ismail, E.I. Akpan, A.A. Hassen, Quest for environmentally sustainable materials: a case for animal-based fillers and fibers in polymeric biocomposites, Compos. Part A Appl. Sci. Manuf. 183 (2024) 108216, https://doi.org/10.1016/j.compositesa.2024.108216.

[282] J.M. Rosales, C. Cejudo, L. Verano, L. Casas, C. Mantell, E.J. Martínez De La Ossa, Supercritical Impregnation of PLA Filaments with Mango Leaf Extract to Manufacture Functionalized Biomedical Devices by 3D Printing, Polymers (basel) 13 (2021) 2125, https://doi.org/10.3390/polym13132125.

[283] S.S. Ahmed, A.A. Abdul-Hamead, E.H. Flaieh, S.A. Abdulhameed, Effect of seed husk waste powder on the PLA medical thread properties fabricated *via* 3D printer, Curved and Layered Structures 11 (2024) 20220222, https://doi.org/10.1515/cls-2022-0222.

[284] N. Cakir Yigit, I. Karagoz, A review of recent advances in bio-based polymer composite filaments for 3D printing, Polym.-Plast. Technol. Mater. 62 (2023) 1077–1095, https://doi.org/10.1080/25740881.2023.2190799.

[285] F. Burla, Y. Mulla, B.E. Vos, A. Aufderhorst-Roberts, G.H. Koenderink, From mechanical resilience to active material properties in biopolymer networks, Nat. Rev. Phys. 1 (2019) 249–263, https://doi.org/10.1038/s42254-019-0036-4.

[286] J. Korpela, A. Kokkari, H. Korhonen, M. Malin, T. Närhi, J. Seppälä, Biodegradable and bioactive porous scaffold structures prepared using fused deposition modeling, J. Biomed. Mater. Res. B Appl. Biomater. 101B (2013) 610–619, https://doi.org/10.1002/jbm.b.32863.

[287] G. Guggenbiller, S. Brooks, O. King, E. Constant, D. Merckle, A.C. Weems, 3D Printing of Green and Renewable Polymeric Materials: Toward Greener Additive Manufacturing, ACS Appl. Polym. Mater. 5 (2023) 3201–3229, https://doi.org/10.1021/acsapm.2c02171.

[288] J. Krause, V. Domsta, M. Ulbricht, P. Schick, A. Seidlitz, A case study to investigate the influence of extrusion temperature, 3D printing parameters and the use of antioxidants on the degradation of dexamethasone, J Drug Deliv Sci Technol 92 (2024) 105394, https://doi.org/10.1016/j.jddst.2024.105394.

[289] S. Tajvar, A. Hadjizadeh, S.S. Samandari, Scaffold degradation in bone tissue engineering: an overview, Int. Biodeterior. Biodegradation 180 (2023) 105599, https://doi.org/10.1016/j.ibiod.2023.105599.

[290] T.S.S. Carvalho, N. Ribeiro, P.M.C. Torres, J.C. Almeida, J.H. Belo, J.P. Araújo, A. Ramos, M. Oliveira, S.M. Olhero, Magnetic polylactic acid-calcium phosphate-based biocomposite as a potential biomaterial for tissue engineering applications, Mater. Chem. Phys. 296 (2023) 127175, https://doi.org/10.1016/j.matchemphys.2022.127175.

[291] F. Chen, J. Han, Z. Guo, C. Mu, C. Yu, Z. Ji, L. Sun, Y. Wang, J. Wang, Antibacterial 3D-printed Silver Nanoparticle/Poly Lactic-Co-Glycolic Acid (PLGA) Scaffolds for Bone Tissue Engineering, Materials 16 (2023) 3895, https://doi.org/10.3390/ma16113895.

[292] G.L. Koons, A.G. Mikos, Progress in three-dimensional printing with growth factors, J. Control. Release 295 (2019) 50–59, https://doi.org/10.1016/j.jconrel.2018.12.035.

[293] C. Yao, Y. Lai, Y. Chen, C. Cheng, Bone Morphogenetic Protein-2-Activated 3D-Printed Polylactic Acid Scaffolds to Promote Bone Regrowth and Repair, Macromol. Biosci. 20 (2020) 2000161, https://doi.org/10.1002/mabi.202000161.

[294] E. Mystiridou, A.C. Patsidis, N. Bouropoulos, Development and Characterization of 3D Printed Multifunctional Bioscaffolds based on PLA/PCL/HAp/BaTiO3 Composites, Appl. Sci. 11 (2021) 4253, https://doi.org/10.3390/app11094253.

[295] M. Baechle-Clayton, E. Loos, M. Taheri, H. Taheri, Failures and flaws in Fused Deposition Modeling (FDM) Additively Manufactured Polymers and Composites, Journal of Composites Science 6 (2022) 202, https://doi.org/10.3390/jcs6070202.

[296] M. Shahbazi, H. Jäger, Current Status in the utilization of Biobased Polymers for 3D Printing Process: a Systematic Review of the Materials, Processes, and Challenges, ACS Appl Bio Mater 4 (2021) 325–369, https://doi.org/10.1021/acsabm.0c01379.

[297] S. Abdella, S.H. Youssef, F. Afinjuomo, Y. Song, P. Fouladian, R. Upton, S. Garg, 3D Printing of Thermo-Sensitive Drugs, Pharmaceutics 13 (2021) 1524, https://doi.org/10.3390/pharmaceutics13091524.

[298] M.R. de Campos, A.C. dos Reis, Effect of post-processing on the mechanical properties of polymers printed by the fused filament fabrication method used as prosthodontic materials and dental biomaterials: a systematic review, Polym. Bull. 81 (2024) 2001–2021, https://doi.org/10.1007/s00289-023-04816-3.

[299] T.R. Klein, A. Kirillova, K. Gall, M.L. Becker, Influence of post-processing on the properties of 3D-printed poly (propylene fumarate) star polymer hydroxyapatite nanocomposites, RSC Appl. Polym. 1 (2023) 73–81, https://doi.org/10.1039/d3lp00013c.

[300] K. Gupta, K. Meena, Artificial bone scaffolds and bone joints by additive manufacturing: a review, Bioprinting 31 (2023) e00268, https://doi.org/10.1016/j.bprint.2023.e00268.

[301] B. Aloyaydi, S. Sivasankaran, A. Mustafa, Investigation of infill-patterns on mechanical response of 3D printed poly-lactic-acid, Polym. Test. 87 (2020) 106557, https://doi.org/10.1016/j.polymertesting.2020.106557.

[302] M. Doshi, A. Mahale, S. Kumar Singh, S. Deshmukh, Printing parameters and materials affecting mechanical properties of FDM-3D printed Parts: Perspective and prospects, Mater. Today Proc. 50 (2022) 2269–2275, https://doi.org/10.1016/j.matpr.2021.10.003.

[303] A.A. Ansari, M. Kamil, Effect of print speed and extrusion temperature on properties of 3D printed PLA using fused deposition modeling process, Mater. Today Proc. 45 (2021) 5462–5468, https://doi.org/10.1016/j.matpr.2021.02.137.

[304] Y. Zhang, B. Jin, W. Zhong, Experimental investigation on mixing and segregation behavior of biomass particle in fluidized bed, Chem. Eng. Process. 48 (2009) 745–754, https://doi.org/10.1016/j.cep.2008.09.004.

[305] R. Sajjad, S.T. Chauhdary, M.T. Anwar, A. Zahid, A.A. Khosa, M. Imran, M. H. Sajjad, A review of 4D printing – Technologies, shape shifting, smart polymer based materials, and biomedical applications, Adv. Ind. Eng. Polym. Res. 7 (2024) 20–36, https://doi.org/10.1016/j.aiepr.2023.08.002.

[306] D.G. Zisopol, M. Tănase, A.I. Portoacă, Innovative strategies for Technical-Economical Optimization of FDM Production, Polymers (basel) 15 (2023) 3787, https://doi.org/10.3390/polym15183787.

[307] M.J. Buehler, Generative Retrieval-Augmented Ontologic Graph and Multiagent strategies for Interpretive Large Language Model-based Materials Design, ACS Eng. Au 4 (2024) 241–277, https://doi.org/10.1021/acsengineeringau.3c00058.

[308] H. Park, Z. Li, A. Walsh, Has generative artificial intelligence solved inverse materials design? Matter 7 (2024) 2355–2367, https://doi.org/10.1016/j.matt.2024.05.017.

[309] R. Pugliese, S. Badini, E. Frontoni, S. Regondi, Generative Artificial Intelligence for advancing Discovery and Design in Biomateriomics, Intell. Comput. 4 (2025) 0117, https://doi.org/10.34133/icomputing.0117.

[310] X. Zheng, X. Zhang, T.-T. Chen, I. Watanabe, Deep Learning in Mechanical Metamaterials: from Prediction and Generation to Inverse Design, Adv. Mater. 35 (2023) 2302530, https://doi.org/10.1002/adma.202302530.

[311] W.L. Ng, G.L. Goh, G.D. Goh, J.S.J. Ten, W.Y. Yeong, Progress and Opportunities for Machine Learning in Materials and Processes of Additive Manufacturing, Adv. Mater. 36 (2024) 2310006, https://doi.org/10.1002/adma.202310006.

[312] S. Badini, S. Regondi, R. Pugliese, Enhancing mechanical and bioinspired materials through generative AI approaches, Next Materials 6 (2025) 100275, https://doi.org/10.1016/j.nxmate.2024.100275.

[313] T. Wang, J. Fan, P. Zheng, An LLM-based vision and language cobot navigation approach for Human-centric Smart Manufacturing, J. Manuf. Syst. 75 (2024) 299–305, https://doi.org/10.1016/j.jmsy.2024.04.020.

[314] C.S. Magnus, M. Venschott, Towards a GPT-Based Lean Manufacturing consultant for Manufacturing Optimization, Procedia CIRP 130 (2024) 167–176, https://doi.org/10.1016/j.procir.2024.10.072.

[315] A. Eslaminia, A. Jackson, B. Tian, A. Stern, H. Gordon, R. Malhotra, K. Nahrstedt, C. Shao, FDM-Bench: a Comprehensive Benchmark for evaluating Large Language Models in Additive Manufacturing Tasks, Manuf. Lett. 44 (2025) 1415–1424, https://doi.org/10.48550/arXiv.2412.09819.

[316] S. Badini, S. Regondi, E. Frontoni, R. Pugliese, Assessing the capabilities of ChatGPT to improve additive manufacturing troubleshooting, Adv. Ind. Eng. Polym. Res. 6 (2023) 278–287, https://doi.org/10.1016/j.aiepr.2023.03.003.

[317] R. Pugliese, S. Badini, S. Regondi, Words to Matter: a Comparative Study for developing Intelligent Design and Manufacturing of 3D Materials based on Large Language Models, in: In: 2024 IEEE International Conference on Metrology for EXtended Reality, Artificial Intelligence and Neural Engineering (MetroXRAINE), 2024, pp. 600–605, https://doi.org/10.1109/MetroXRAINE62247.2024.10796454.

[318] V. Shanmugam, O. Das, K. Babu, U. Marimuthu, A. Veerasimman, D.J. Johnson, R.E. Neisiany, M.S. Hedenqvist, S. Ramakrishna, F. Berto, Fatigue behaviour of FDM-3D printed polymers, polymeric composites and architected cellular

materials, Int. J. Fatigue 143 (2021) 106007, https://doi.org/10.1016/j.ijfatigue.2020.106007.

[319] O.A. Mohamed, S.H. Masood, J.L. Bhowmik, Optimization of fused deposition modeling process parameters: a review of current research and future prospects, Adv. Manuf. 3 (2015) 42–53, https://doi.org/10.1007/s40436-014-0097-7.

[320] K. Özsoy, B. Aksoy, Real-Time Data Analysis with Artificial Intelligence in Parts Manufactured by FDM Printer using image Processing Method, J. Test. Eval. 50 (2022) 629–645, https://doi.org/10.1520/JTE20210125.

[321] Y.-C. Hsu, Z. Yang, M.J. Buehler, Generative design, manufacturing, and molecular modeling of 3D architected materials based on natural language input, APL Mater. 10 (2022) 041107, https://doi.org/10.1063/5.0082338.

[322] M. Elbadawi, H. Li, S. Sun, M.E. Alkahtani, A.W. Basit, S. Gaisford, Artificial intelligence generates novel 3D printing formulations, Appl. Mater. Today 36 (2024) 102061, https://doi.org/10.1016/j.apmt.2024.102061.

[323] H. Wei, L. Tang, H. Qin, H. Wang, C. Chen, Y. Li, C. Wang, Optimizing FDM 3D printing parameters for improved tensile strength using the Takagi–Sugeno fuzzy neural network, Mater. Today Commun. 38 (2024) 108268, https://doi.org/10.1016/j.mtcomm.2024.108268.

[324] D. Veeman, S. Sudharsan, G.J. Surendhar, R. Shanmugam, L. Guo, Machine learning model for predicting the hardness of additively manufactured acrylonitrile butadiene styrene, Mater. Today Commun. 35 (2023) 106147, https://doi.org/10.1016/j.mtcomm.2023.106147.

[325] J. Zhu, Z. Su, Q. Wang, Z. Lan, F. Siu-fai Chan, Z. Han, Z. Wang, S. Wing-fai Wong, A. Chi-fung Ngan, Surface quality prediction and quantitative evaluation of process parameter effects for 3D printing with transfer learning-enhanced gradient-boosting decision trees, Expert Syst Appl 237 (2024) 121478. doi: 10.1016/j.eswa.2023.121478.

[326] D.A.J. Brion, M. Shen, S.W. Pattinson, Automated recognition and correction of warp deformation in extrusion additive manufacturing, Addit. Manuf. 56 (2022) 102838, https://doi.org/10.1016/j.addma.2022.102838.

[327] M. Tănase, A.I. Portoacă, A. Diniță, G. Brănoiu, F. Zamfir, E.-E. Sirbu, C. Călin, Optimizing Mechanical Properties of Recycled 3D-printed PLA Parts for Sustainable packaging Solutions using Experimental Analysis and Machine Learning, Polymers (basel) 16 (2024), https://doi.org/10.3390/polym16233268.

[328] A. Petsiuk, J.M. Pearce, Open Source Filament Diameter Sensor for Recycling, Winding, and Additive Manufacturing Machines, J. Manuf. Sci. Eng. 143 (2021), https://doi.org/10.1115/1.4050762.

[329] F. Altun, A. Bayar, A.K. Hamzat, R. Asmatulu, Z. Ali, E. Asmatulu, AI-Driven Innovations in 3D Printing: Optimization, Automation, and Intelligent Control, Journal of Manufacturing and Materials Processing 9 (2025), https://doi.org/10.3390/jmmp9100329.

[330] M. Farhan Khan, A. Alam, M. Ateeb Siddiqui, M. Saad Alam, Y. Rafat, N. Salik, I. Al-Saidan, Real-time defect detection in 3D printing using machine learning, Mater. Today Proc. 42 (2021) 521–528, https://doi.org/10.1016/j.matpr.2020.10.482.

[331] A. Saluja, J. Xie, K. Fayazbakhsh, A closed-loop in-process warping detection system for fused filament fabrication using convolutional neural networks, J. Manuf. Process. 58 (2020) 407–415, https://doi.org/10.1016/j.jmapro.2020.08.036.

[332] Y. AbouelNour, N. Gupta, Assisted defect detection by in-process monitoring of additive manufacturing using optical imaging and infrared thermography, Addit. Manuf. 67 (2023) 103483, https://doi.org/10.1016/j.addma.2023.103483.

[333] M. Najjartabar Bisheh, S.I. Chang, S. Lei, A layer-by-layer quality monitoring framework for 3D printing, Comput Ind Eng 157 (2021) 107314, https://doi.org/10.1016/j.cie.2021.107314.

[334] V. Kadam, S. Kumar, A. Bongale, S. Wazarkar, P. Kamat, S. Patil, Enhancing Surface Fault Detection using Machine Learning for 3D Printed Products, Applied System Innovation 4 (2021) 34, https://doi.org/10.3390/asi4020034.

[335] Z. Jin, Z. Zhang, G.X. Gu, Automated Real-Time Detection and Prediction of Interlayer Imperfections in Additive Manufacturing Processes using Artificial Intelligence, Adv. Intell. Syst. 2 (2020) 1900130, https://doi.org/10.1002/aisy.201900130.

[336] V. Yakubov, H. Ostergaard, S. Bhagavath, C.L.A. Leung, J. Hughes, E. Yasa, M. Khezri, S.K. Löschke, Q. Li, A.M. Paradowska, Recycled aluminium feedstock in metal additive manufacturing: a state of the art review, Heliyon 10 (2024), https://doi.org/10.1016/j.heliyon.2024.e27243.

[337] S. Gantenbein, E. Colucci, J. Käch, E. Trachsel, F.B. Coulter, P.A. Rühs, K. Masania, A.R. Studart, Three-dimensional printing of mycelium hydrogels into living complex materials, Nat. Mater. 22 (2023) 128–134, https://doi.org/10.1038/s41563-022-01429-5.

[338] P.S. Klee, C. Vazquez-Martel, L. Florido Martins, E. Blasco, Designing Sustainable Polymers: Lactate Esters for 3D Printing and Upcycling, ACS Appl Polym Mater 6 (2024) 935–942. doi:10.1021/acsapm.3c02497.