REVIEW

The role of 3D printing in advancing biotechnology and bioengineering: A review

Ismail Agir [1]

[1] Istanbul Medeniyet University, Department of Bioengineering, Faculty of Engineering and Natural Sciences, 34700, **Istanbul, Türkiye**
ROR ID: 05j1qpr59
* **Corresponding author**: E-mail: agr.isml@gmail.com; Ph.: +90 266 552 2903

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Abstract

Three-dimensional (3D) printing, a subset of additive manufacturing technologies, has attracted significant attention from researchers for both laboratory-based and on-site prototyping since its widespread adoption. Its adaptability and versatility have made it an essential tool across various disciplines, particularly in biotechnology and bioengineering. While conventional manufacturing methods can offer precise material control and compatibility with biological fluids, they often pose significant challenges, such as high costs and the requirement for large, complex setups. These constraints limit their accessibility for the experimental needs of biotechnology and bioengineering. However, 3D printers, with their high adaptability and ability to process a wide range of materials, have proven to be remarkably effective in resolving these challenges. Their capability to create custom parts and structures while maintaining compatibility with biomaterials and fluids has opened new possibilities not only in tissue engineering, drug development, and biomedical device fabrication, but also across the broader fields of biotechnology, biochemistry, and related sciences. When examining the basic concept and development timeline of 3D printers, it becomes clear that emerging trends in artificial intelligence, robotics, and digitalization are expected to further accelerate their integration into real-world applications. These ongoing advancements are likely to benefit laboratories and production centers involved in biotechnology by speeding up experiments, paving the way for rapid production and testing, and making complex biofabrication processes more accessible and automated, including in areas like tissue engineering and personalized medicine.

Keywords: 3D printing, additive manufacturing, bioengineering, biofluids, instrumentation, rapid prototyping

Introduction

Additive manufacturing refers to the process of building a product by adding layers of homogeneous or different materials in a numerically controlled and stable manner, ensuring they are mechanically bonded and resistant to separation over time. Additive manufacturing, by definition, involves building an object by adding material layer by layer during the production process, in contrast to traditional (subtractive) manufacturing, which shapes the final product by removing material from larger blocks. As a result, one of the primary benefits of additive manufacturing is the significant reduction of waste material compared to traditional methods (Monfared et al., 2023; Narsimhachary & Kalyan Phani, 2024; Zhou et al., 2024).

The first patent application (stereolithography, SLA) in the field of additive manufacturing was filed in 1984 focused on computer-controlled stereolithography (United States Patent No. US4575330A, 1986). Four years later, the prototype was commercialized, marking a significant milestone in the history of AM with the process of solidifying liquid photopolymers using ultraviolet (UV) lasers guided by computer-controlled 3D motion mechanisms. Later, Fused Deposition Modeling (FDM or Fused Filament Fabrication, FFF) emerged. These techniques rely on combining thermoplastics or materials with similar thermal characteristics that are heated to their melting point, extruded into thin layers, and solidified through rapid cooling (Choi et al., 2011).

A pivotal development occurred with the RepRap project (initiated in 2005), which aimed to create self-replicating 3D printers capable of manufacturing their own components (Jones et al., 2011). The success of the RepRap project led to a rapid expansion of the open-source ecosystem surrounding 3D printing. The availability of easy-to-print and less hazardous materials like PLA after 2010 made printers more accessible, eventually reaching household use. Additionally, the expiration of FDM patents in 2009 and SLA patents in 2014 significantly contributed to the growth of makers developing 3D printers, further accelerating the widespread adoption of technology (United States Patent No. US5121329A, 1992; United States Patent No. US4575330A, 1986). Figure 1 presents simplified schematics illustrating the FDM and resin-based printing techniques.

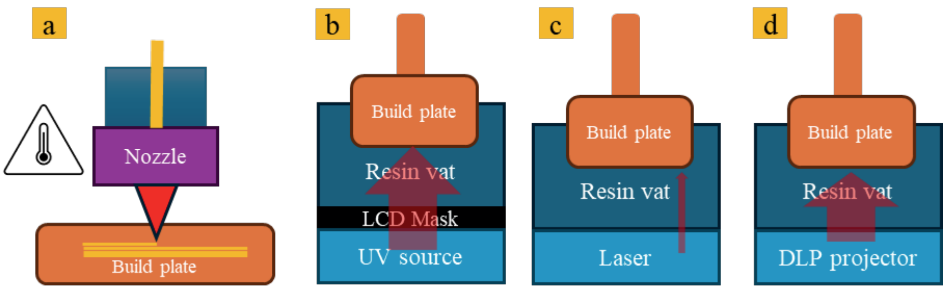

Figure 1. Simple schematics of basic 3d printing techniques, A: FDM, B: MSLA (Masked Stereolithography), C: SLA, D: DLP (Digital Light Processing)

Table 1 compares various 3D printing methods (excluding bioprinting). FDM is typically favored for its affordability and wide range of material options, making it ideal for large prints. Resin-based techniques, though more sensitive and expensive, offer higher precision, with MSLA being a more cost-effective alternative. Powder-based methods are faster and more sensitive but tend to be the most expensive, especially when combined with metal powder melting.

Table 1. Comparison of the main features of main 3D printing techniques.

Method	Printing principle and materials	Resolution	Cost
FDM	Extrudes various thermoplastic filaments layer by layer	Moderate	Low
SLA	Cures photopolymer liquid resin using UV light	Very High	Moderate
MSLA	Cures resin using a masked LCD screen to project light	Very High	Moderate-Low
SLS (Selective Laser Sintering)	Fuses powder material (polymer, metal) using a laser layer by layer	High	High
DLP	Cures resin layers using digital light projection	Very High	Moderate
MJF (Multi Jet Fusion)	Fuses powder layers using fusing and detailing agents (PA, TPU)	High	High
EBM (Electron Beam Melting)	Melts metal powder using an electron beam in vacuum	High	Very High

In this paper, three-dimensional printing technologies, which are becoming increasingly vital tools in bioscience due to the unique advantages they offer, are reviewed under the sorted headings outlined in Figure 2.

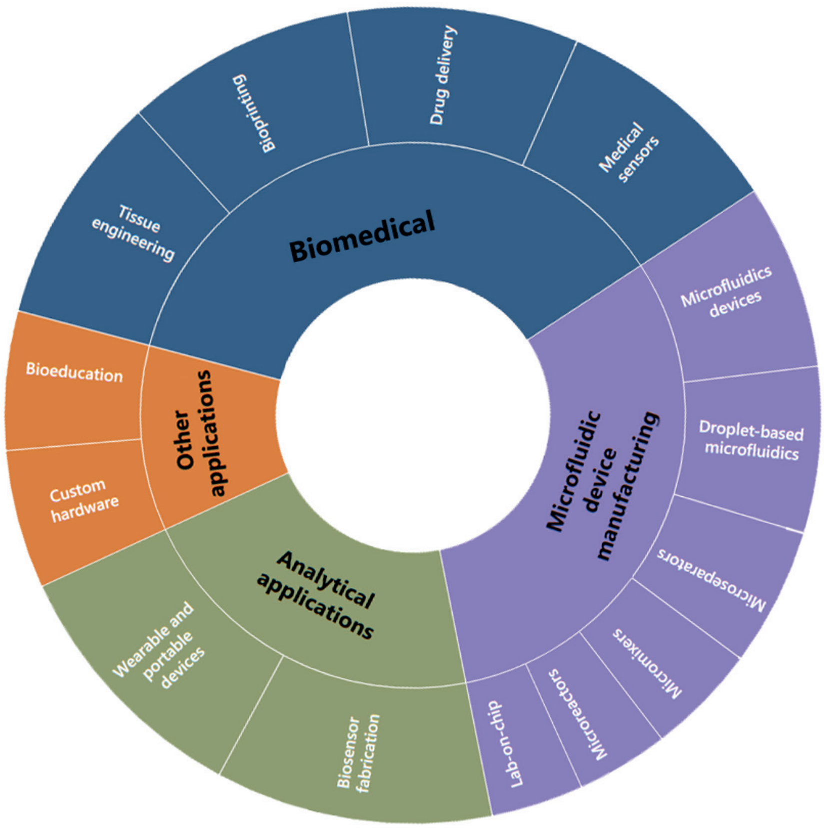

Figure 2. Key applications of 3D printing technologies in bioscience.

3D printers in microfluidic device manufacturing

Microfluidic devices: The conventional method for producing microfluidic systems typically involved several steps, beginning with molding a poly(dimethylsiloxane) (PDMS) substrate using soft lithography. Although this method is effective, it requires multiple complex steps, specialized expertise, and a well-equipped infrastructure (Bhattacharjee et al., 2016). Compared to classical methods, 3D printing has streamlined the production process by reducing the number of steps and significantly lowering costs (Amin et al., 2016). In this field, as well as from a broader perspective, various 3D printing techniques can be applied. Resin and inkjet printers excel in precision, while MSLA printers offer a balance of accuracy and affordability. On the other hand, FDM printers are more cost-effective but are limited by their lower resolution, making them less suitable for applications requiring fine details (Waheed et al., 2016). 3D printing has enabled the rapid fabrication of microfluidic devices designed for specific applications, particularly in key areas such as biofluid mixing and separation, microreactors, and complex organ-on-chip assemblies. Thanks to the open-source nature of 3D printers, researchers can accelerate experiments by developing customized software and production workflows engineered to meet specific objectives (Y. Zhang et al., 2024).

Droplet-based microfluidics: 3D printers are successfully employed in droplet-based microfluidics, a technology that utilizes various physical actuation methods (e.g., magnetic, ultrasonic, pneumatic, thermal) to regulate droplet generation, making it possible to design custom components integrated into unified microfluidic devices (Aladese & Jeong, 2021; Moragues et al., 2023). Jiao et al. developed a 3D-printed droplet-based microfluidic chip and applied it for PCR detection of miRNA-21 in cellular samples, demonstrating its utility for sensitive and specific biomarker detection in cancer diagnostics (Jiao et al., 2019). Ji et al. developed a customizable microfluidic system using 3D-printed components capable of creating emulsion droplets with desired properties (Ji et al., 2018). Nguyen et al. demonstrated the production of cell-containing hydrogel microspheres by developing a 3D-printed system with an adjustable gap height (Nguyen & Seo, 2022). In one study, the desired surface hydrophobicity was adjusted by leveraging 3D printing's ability to work with various materials (Warr et al., 2021). In pharmaceutical research, 3D-printed droplet-based chips play a prominent role in drug synthesis, screening, and delivery applications (Trinh et al., 2023). Additionally, the droplet microfluidic method has been shown to produce sensors for a wide range of applications by utilizing inks with various functions (Zub et al., 2022).

Micromixers: Micromixers are microfluidic devices used in biochemistry, both in the laboratory and in the field, for preparing homogeneous mixtures before they proceed, and the use of 3D printing for their fabrication has grown in significance (Razavi Bazaz et al., 2024). For example, Borro et al. successfully controlled the capacity and size of drug-loaded hydrogels using the micromixer they developed(Borro et al., 2019). Lavrentieva et al. utilized 3D-printed micromixers to achieve homogeneous mixing of precursors and crosslinkers, enabling the creation of stiffness gradients in photoactive hydrogels, an approach often applied in mechanobiology research (Lavrentieva et al., 2020). Bohr et al. produced nanocomplexes using micromixers they designed, enabling pilot-scale production speeds (Bohr et al., 2017). Researchers have designed micromixers that facilitate the rapid measurement of various biomarkers using portable biosensor systems **(Chan et al., 2016a; B. Liu et al., 2022; Plevniak et al., 2016)**. With rapid prototyping made possible by 3D printers, researchers can now conduct production tests of more efficient micromixers through computer simulation studies (Ammar et al., 2025; Liao et al., 2025; Z. Wang et al., 2023; Yin et al., 2021).

Microseparators: The use of 3D-printed microseparators is common in the separation of biological fluids and solids, serving purposes such as sample preparation, filtration, bioproduct purification, component separation, reaction setup, impurity removal, and diagnostics (Griffin & Pappas, 2023; Marković et al., 2024). In one study, 3D spiral separators were employed for the large-scale separation and extraction of stem cells (Ding et al., 2022). In another study, a different spiral design was developed to separate mammalian ovarian cells into a continuous flow system by incorporating 3D buffers (Enders et al., 2021). Amin et al. developed a portable 3D-printed device for the mass density-based separation of label-free heterogeneous cell mixtures in real-time continuous flow (Amin et al., 2017). Yang et al. harnessed the power of transferrin-receptor affinity to isolate cancer cells from biopsy fluids by modifying the surface of a 3D-printed device (Yang et al., 2023). Schellenberg et al. integrated a 3D-printed microseparator into a bioreactor outlet, eliminating the need for periodically replaced membranes and enabling continuous high-yield purification of monoclonal antibodies produced by cells (Schellenberg et al., 2023). Syed et al. designed a 3D-printed microcyclone separator for efficient and continuous harvesting of microalgae (Syed et al., 2017). With the rise of 3D printers, the development and testing of complex micromixers has become significantly easier (J. Clark et al., 2024; P. Li et al., 2021; Oldach et al., 2024).

Microreactors: Microreactors are all-in-one micro-bioprocessing solutions that garner attention due to their efficiency, scalability, and precise control over reaction conditions (Maier et al., 2020; Shrimal et al., 2020). Cingesar et al. designed a 3D microreactor and connected it to a microseparator to carry out methyl ester conversion under optimal conditions in the production of biodiesel from sunflower oil (Cingesar et al., 2025). One of the advantages of microreactors is the large surface area they offer, enabled by customizable and printable porosity options, which promotes homogeneous catalytic activity in continuous flow systems. Building on this advantage, Baena-Moreno et al. designed a system with internal surfaces in a gyroid geometry, which successfully increased the CO_2 conversion rate by 14% (Baena-Moreno et al., 2021). Alimi et al. similarly utilized a microreactor for flavonoid oxidation, significantly enhancing the reaction rate compared to a traditional batch reactor (Alimi et al., 2020). Ibáñez-de-Garayo et al. designed a microreactor specifically tailored for photocatalysts by creating a multichannel microarray, which evenly distributes light with high transmittance, effectively increasing the surface area (Ibáñez-de-Garayo et al., 2023). The advantages of 3D-printed microreactors are also leveraged in bioreactors, making them ideal for the cultivation of algae and other photosynthetic microorganisms (Castaldello et al., 2019; Podwin & Dziuban, 2017).

Lab-on-chip: Micro total analysis systems (μTAS), also known as lab-on-chips, are microfluidic devices typically used for analytical applications. They are created by integrating various functional units, such as the mixer, separator, and reactor designs previously mentioned, along with microvalves and microconcentrators (Patabadige et al., 2016). In one study, a low-cost flow analyzer for exposome determination from soil samples was developed using 3D printing technology (Cocovi-Solberg et al., 2019). Chiado et al. designed an optical analytical device that enables the detection of protein biomarkers, aiding in the early diagnosis of cancer (Chiadò et al., 2020). Adamski et al. developed a 3D-printed chip capable of performing DNA gel electrophoresis more cost-effectively and quickly (Adamski et al., 2016). 3D microchips are well-suited for artificial organ studies. For instance, in one study, an artificial nervous system chip was created to investigate viral infections in the nervous system (Johnson et al., 2016). Cardiovascular tissues and organs are also the focus of research and study using 3D microchips (Y. S. Zhang et al., 2016). Addario et al. designed a chip with the purpose of mimicking kidney tubule segments, which was used for in vitro tests related to chronic kidney disease (Addario et al., 2024).

3D printers in tissue engineering, bioprinting and biomedical

Bioprinting: Bioprinting refers to the process of combining biological materials to create structures such as tissues, organs, patches, or scaffolds, following principles similar to those of additive manufacturing (Mironov et al., 2006). The most notable difference from other 3D printing techniques is the use of bioinks as building materials (Decante et al., 2021). These bioinks, typically liquid, gel, or composite, are specifically developed to incorporate cells, microorganisms, macromolecules, and hormones (Daly et al., 2021). Additionally, bioprinting utilizes print heads such as various droplet-based microfluidic systems, pressurized syringe tips, pneumatic, or screw extruders, with the screws used to mix the materials for precise biomaterial deposition (Chen et al., 2023). These techniques typically require high-end printers, but with the adoption of photopolymer-based bioinks and high-resolution, low-cost resin printers, they have become more accessible and widely used in many laboratories (Tong et al., 2021). Unlike other 3D printing techniques, bioprinting can be performed directly on living tissues, organisms, or within a viscous medium to apply the bioink without disturbance and in a biocompatible manner (Singh et al., 2020). A viscous medium acts as a support structure in the technique known as submerged printing (H. Li et al., 2021). Additionally, several viscosity-lowering methods are employed to create stable 3D-printed structures while preserving biocompatibility (Colosi et al., 2016).

Tissue engineering and drug delivery: 3D printers are one of the basic tools in tissue engineering, as well as regenerative medicine (Bartolo et al., 2022). Whether using gel, solid polymer, or composite material, 3D printing is one of the most widely utilized techniques in the production of tissue scaffolds (Dutta et al., 2021; Radhakrishnan et al., 2021; Richards et al., 2013; Shao et al., 2019). The scaffold must have adjustable biodegradability and porosity, which is why 3D-printed fabrication is ideal, as it allows for precise control over these factors due to the wide availability of materials, ensuring the scaffold meets the specific requirements for tissue regeneration (An et al., 2015; Stratton et al., 2016; Wen et al., 2017). With 3D printing, scaffolds can be rapidly produced in geometries tailored for clinical applications (Blázquez-Carmona et al., 2021). 3D printers are widely used in cell seeding studies due to their ability to work with hydrogels. For instance, Xue et al. produced scaffolds with varying hardness by modifying 3D printing parameters, providing physical support for the seeded fibroblasts to grow **(Xue et al., 2019)**. Feng et al. achieved uniform and effective cell transplantation using a 3D-printed scaffold made from alginate and gelatin **(Feng et al., 2020)**. Similarly, drug-loaded tissue treatment patches, often created through 3D printing using biodegradable gels and materials, are also widely applied in biomedical treatments (Jang et al., 2021). This approach is also enabling personalized treatments (Manousi et al., 2024; Peng et al., 2017). 3D printers are also utilized in the production of microneedles, which play a crucial role in drug delivery and portable medical diagnostic devices (Detamornrat et al., 2022; Uddin et al., 2020).

Biomedical: 3D printing enables the creation of patient-specific biomedical devices that are ready for clinical use, particularly in fields such as orthopedics (Wong, 2016). 3D printers are being used to create metal alloy medical nails, wires, drug-loaded implants, and even tiny medical robots (Alam et al., 2020; Hari Raj et al., 2023; Honda et al., 2024; Wei et al., 2024; Ye et al., 2020). The use of 3D printing has expanded to larger models, such as customized arm and neck splints and braces, offering time and labor savings while improving efficiency compared to traditional plaster methods (Ambu et al., 2024; Boolos et al., 2022; J. Li & Tanaka, 2018). The use of 3D printers in dental applications has shown successful clinical outcomes and is becoming increasingly widespread as both printer and material costs decrease, along with advancements in material research (Anadioti et al., 2020; Majeed et al., 2024; Tichá et al., 2024; van Noort, 2012). 3D printers are demonstrating significant potential in pharmaceutical drug research, facilitating the discovery of new drugs and enabling more personalized approaches to treatment development (Amekyeh et al., 2021; Michalski & Ross, 2014; Pugliese et al., 2021). There are also notable applications in otolaryngology, including the creation of eardrums and cartilage tissue replacements using 3D printing (Hu et al., 2023; Pugliese et al., 2021). 3D printers also serve an important role in advancing biomedical studies, particularly involving cell culture and cell line growth **(Bruno et al., 2019; Herreros-Pomares et al., 2021; Lerman et al., 2018)**.

Sensors: The role of 3D printers in biomedical sensor fabrication is also worth mentioning, such as a flexible wearable sensor that measures shoulder movement limitations, a piezoelectric insole that performs gait analysis, haptic devices that include a soft pressure sensor, and wearable biomechanical sensors made of a conductive transparent gel (Dimo et al., 2024; Latsch et al., 2024; Ntagios et al., 2020; Zeng et al., 2025).

Analytical applications of 3D printers

Biosensor fabrication: The production of most biosensors involves making functional modifications to a substrate material to enable specific biosensing capabilities, often incorporating multiple layers that work together to generate an electrically readable or optically visible signal (Katey et al., 2023). 3D printers are poised to play a significant role in this field due to their ability to work with materials that possess a wide range of functional biochemical and physical properties, such as bioinks, as well as those exhibiting conductive, magnetic, and optical activities (Byrne et al., 2024). For example, Hussaini et al. produced and modified electrodes for dopamine detection using a 3D printer, while Tiwari et al. fabricated microporous electrodes with a 3D printer to detect antibiotics in tissue scaffolds (Hussaini et al., 2024; Tiwari et al., 2024). Glasco et al. produced the electrodes of a new enzyme-free biosensor by 3D printing carbon material (Glasco et al., 2024). In another study, Wang et al. utilized a bioreceptor printed with bioink containing liver microtissue cells for the detection of deoxynivalenol (N. Wang et al., 2025).

Wearable and portable devices: 3D printers are also employed to create the necessary components that enable biosensors to function as portable or wearable devices (Ozer et al., 2022a). Examples include the production of microneedles for biomedical sampling, integration of sensor elements into compact structures such as specialized equipment like heaters and sampling chambers, and optical microfluidic devices that allow colorimetric measurements using a smartphone (Biswas et al., 2024; Chan et al., 2016b; Xu et al., 2024). 3D printers also facilitate the *in-situ* application of biosensors in various fields such as environmental monitoring, agriculture, and food safety (Ataei Kachouei et al., 2025; Ozer et al., 2024; Q. Zhang et al., 2021).

Custom laboratory equipment and educational tools produced using 3D printers

3D printed hardware: With the rise of digital manufacturing, also known as 3D printing, synchronized with the expansion of the open-source software and hardware ecosystem, researchers have increasingly started creating their own devices for both emergencies and regular use (Baden et al., 2015; Ozer et al., 2022b). For instance, Behrens et al. fabricated a mini peristaltic pump; Holland et al. developed a custom syringe pump; Traciak et al. created a surface tension meter; Pechlivani et al. built a bioreactor; Sule et al. designed a centrifuge, Wilson et al. produced a micropipette, and Chagas et al. designed a fluorescence microscopy platform (Behrens et al., 2020; Chagas et al., 2017; Pechlivani et al., 2023; Sule et al., 2019; Traciak et al., 2021; Wilson & Mace, 2017).

3D printing in bioeducation: 3D printing has emerged as a standout tool in bio-related science education (bioeducation), offering innovative and interactive real-world objects that enhance students' understanding of the educational curriculum. For example, Gul et al. conducted a controlled educational experiment by creating 3D models of biomolecules in living organisms, revealing a clear difference in student comprehension (Gul & Yalinkilic, 2025). Lim et al. incorporated 3D printed models in anatomy lectures (Lim et al., 2016), while Augusto et al. used them in a cell biology course (Augusto et al., 2016). Boll et al. highlighted the usefulness of 3D models in synthetic biology within STEM education **(Oss Boll et al., 2023)**. Pinger et al. have highlighted the superior role of 3D printers in chemistry education (Pinger et al., 2020), and similarly, Renner et al. utilized 3D microfluidics in teaching continuous flow reactors and photoreactions (Renner & Griesbeck, 2020).

Challenges and limitations in using 3D printers

Despite the unique advantages, the use of 3D printers in biosciences also presents some limitations depending on the method applied. For example, in FDM printers, gaps may form between layers due to the way molten material is extruded and shaped. Although these gaps are typically smaller than 0.1 mm and not large enough to support biofilm formation, water molecules or chemical and biological contaminants can adhere to them (Aguado-Maestro et al., 2021). This makes it difficult to fully clean the printed object, especially between the layers. Post-printing surface finishing modifications, such as polishing, can help eliminate these gaps and improve the structure's suitability for bioscience applications. Notably, resin-based printers tend to exhibit fewer issues with interlayer gaps, offering a potential advantage in this regard. Additionally, high-temperature sterilization methods are often unsuitable for FDM-printed objects, necessitating the use of alternative sterilization techniques (Wiseman et al., 2022).

Another significant challenge is cost. While metal 3D printers used in biomedical and dental applications offer advantages over traditional manufacturing methods, they remain relatively expensive to acquire and operate. Additionally, although common materials and consumables used in 3D printing are generally affordable, specialized materials with advanced properties—such as high electrical conductivity, transparency, UV resistance, or a high Young's modulus or elasticity coefficient—come at a much higher cost. This can limit the accessibility of advanced applications and increase the overall expense of research or production on specific bio-applications (Lee et al., 2017; B. Li et al., 2023; Ma et al., 2023; Sachyani Keneth et al., 2021).

PLA, one of the most widely used materials in FDM printers, is typically derived from corn syrup and is biodegradable under controlled conditions. However, it does not break down as easily in natural environments as other biodegradable polymers like PCL (polycaprolactone) or PVA (polyvinyl alcohol). To address this, increasing attention is being given to materials enhanced with additives such as cellulose and lignin, which offer improved biodegradability and sustainability (Choe et al., 2022). In resin-based printers, the trend is shifting toward the use of bio-based photopolymers, which are gaining popularity for their environmentally friendly properties and compatibility with biological applications (Skliutas et al., 2020; Voet et al., 2021).

It is well-documented that mechanically formed microplastic particles can be dispersed into the air during the FDM printing process. However, when using PLA, this does not pose a significant health risk in spaces with normal ventilation. In contrast, materials like ABS release toxic fumes when subjected to high temperatures, making proper ventilation an absolute necessity (Gu et al., 2019; Salthammer, 2022). Similarly, resin printers emit harmful gases, including volatile organic compounds, during the printing process. To address this, many are equipped with HEPA and activated carbon filters to reduce emissions and improve safety during operation (Davis et al., 2019; Garcia-Gonzalez et al., 2024). Another consideration with resin printing is the need for post-processing, including additional curing and washing of the printed objects. The washing process typically involves ethyl alcohol, which can be hazardous if not handled properly. To address this, water-washable, bio-based resins are increasingly being used as a safer and more eco-friendly alternative (Y. Liu et al., 2024).

Conclusions

3D printers have attracted significant interest from the scientific community since they became widespread. The inherent precision of common 3D printing techniques and the variety of materials available, including biomaterials, have allowed them to quickly find a place in the field of bioengineering. In today's open-source digital era, biological products and related components within the biotechnology ecosystem—such as reactors, sensors, microfluidics, wearable devices, implants, and prostheses—are increasingly benefiting from the advantages of computerization thanks to 3D printing technology. With this unique output, researchers are exploring the vast potential of 3D printers across various fields, ranging from education to the synthesis of basic biochemical molecules. As they integrate new material handling techniques into their work, researchers are uncovering novel ways to enhance productivity, reduce research costs, and increase innovation and precision in bioengineering applications.

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Conflict of interest

The author declares no conflict of interest.

Data availability statement

Data sharing is not applicable to this review article as no datasets were generated or analyzed during the current study.

Ethics committee approval

Ethics committee approval is not required for this study.

Authors' contribution statement

Ismail Agir wrote and designed this article.

ORCID and emails of the authors

Ismail Agir | ORCID: 0000-0003-2341-9245 | agr.isml@gmail.com

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