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# From design to detection: a review of 3d printing materials, electrochemical sensors, and biosensors

ARIELLY CARDOSO, JÉSSICA R. CAMARGO, RODRIGO A.A. MUÑOZ & BRUNO C. JANEGITZ

**Abstract:** Three-dimensional (3D) printing, also referred to as additive manufacturing, has emerged as a practical approach for managing accessible production processes aimed at fabricating widely used components and objects commonly found in daily life. The technique is distinguished by its ability to produce intricate designs, as well as its cost-effectiveness and rapid manufacturing capabilities. Moreover, it is relatively user-friendly, requiring the operator to create a digital model of the desired component using CAD (Computer-Aided Design) software, which is then exported into a file format compatible with the printer. Within the realm of additive manufacturing, a broad array of techniques is available, each suitable for processing different materials. Among the available additive manufacturing techniques, fused deposition modeling (FDM) is the most widely used for fabricating electrochemical devices because of its simplicity, low cost, and compatibility with conductive polymer composites. The fabrication of electrochemical sensors and biosensors has attracted increasing attention owing to the rapid prototyping and design flexibility offered by FDM. The purpose of this review is to discuss recent advances in FDM-printed electrochemical sensors and biosensors, focusing on conductive filament compositions, fabrication strategies, electrochemical performance, and emerging applications. Current challenges and future perspectives for wearable and sustainable sensing platforms are highlighted.

**Key words:** Additive manufacturing, technology, prototyping, electrochemical sensors, 3D printing.

## INTRODUCTION

### What is 3D printing?

Three-dimensional (3D) printing, also referred to as additive manufacturing, has been widely employed over the past decades for the fabrication of different materials through computer-aided design (CAD) modeling. This technology has revolutionized several engineering fields by enabling the modification of product models with unprecedented flexibility. Consequently, numerous strategies for additive manufacturing have been proposed, mainly due to the significant advantage of reducing production time (Arefin et al. 2021).

The term encompasses a broad range of innovations across multiple disciplines, with virtually unlimited possibilities for fabricating parts using diverse precursors. The adoption of different 3D printing methods has attracted growing attention from both industry and academia, not only for the fabrication of new devices but also for the modification of existing materials (Mahapatra et al. 2024).

This technology has expanded the range of achievable geometries, enabling the production of intricate, complex designs that would conventionally require highly elaborate modeling. The challenges that previously limited such fabrications were overcome by the development of equipment capable of manufacturing objects using 3D modeling tools and specialized software. Moreover, a wide variety of materials can be processed, including ceramics, thermoplastics, metals, resins, and other composites (Agrawaal & Thompson 2021, Zhai et al. 2025).

With the rapid advancement of 3D printing technologies, several techniques have been established for producing functional objects with different applications. The most widely used include fused deposition modeling (FDM), stereolithography (SLA), digital light processing (DLP), selective laser sintering (SLS), direct metal laser sintering (DLMS), polyjet, selective laser melting (SLM), and electron beam melting (EBM) (Volpato 2021, Jiang et al. 2022).

Stereolithography is a pioneering technique in additive manufacturing, operating on the principle of photopolymerization, where resin is solidified through light absorption. A critical factor for efficient printing is the energy density applied to the material, ensuring the layer-by-layer construction without interruptions. Post-processing usually involves chemical treatment to remove excess resin, followed by ultraviolet (UV) curing to enhance structural stability (Kafle et al. 2021, Pu et al. 2023). These procedures, however, can be further optimized to reduce production time (Kafle et al. 2021, Pu et al. 2023).

Similar to SLA, DLP also employs a photopolymeric resin tank; however, the main distinction lies in the light exposure system. In DLP, a digital projection screen is used to cure the resin layer by layer, with each projected image defining the geometry of the part (Guggenbiller et al. 2023).

SLS, in turn, uses a laser beam to fuse polymer powder in a closed chamber, a principle that differs from other common techniques (Nofar et al. 2022). Different particle binding mechanisms enable the transformation of powdered feedstock into three-dimensional objects (Kafle et al. 2021). Materials such as ceramics, polymers, and even renewable resource-derived powders can be employed due to their availability in particulate form (Yu et al. 2021).

Preheating is a crucial step in this process, as uneven heat distribution can significantly affect the quality of the final piece. To overcome the limitation of SLS in processing only polymers, DLMS was developed for fabricating parts from metal-based powders using laser irradiation. The main advantage of this approach is the high geometric accuracy, as the powder is deposited layer by layer to produce high-resolution structures (Kafle et al. 2021, Yu et al. 2021, Hassan et al. 2022, Sedlacek et al. 2023).

Among the laser-based additive manufacturing techniques, SLM is distinguished by its ability to melt regions of a powder bed using thermal energy selectively. In practice, the laser fuses the outer regions of the powder layers before consolidating the inner volume of the material (Volpato 2021). Unlike powder-based processes, the PolyJet technique employs jetting of liquid photopolymeric resins onto a substrate. The polymer droplets are deposited sequentially and solidified immediately under ultraviolet irradiation, which prevents imperfections and reduces material loss (Volpato 2021).

Driven by industrial demand for faster and more versatile additive manufacturing routes, the EBM technique was developed. It is conceptually similar to laser-based methods but relies on an electron beam, offering higher scanning

speeds and elevated processing temperatures. However, its main drawback compared to other approaches is the reduced accuracy of the final product due to the extremely high processing speed (Volpato 2021).

Among all available techniques, FDM remains the most widely used because of its advantages, including mass production of objects and prototypes, relatively low cost, ease of model design, and rapid prototyping (Contreras-Naranjo et al. 2021, Abdalla & Patel 2021). This technique typically employs thermoplastic materials, where the print head is heated until the polymer reaches its melting point and is deposited layer by layer onto the build platform. Unlike resin-based methods, FDM does not require UV curing, since the processed materials are usually solid at room temperature (Sampaio et al. 2022, Flores et al. 2022).

## History of Additive Manufacturing

The concept of 3D printing emerged in the 1980s, when researcher Hideo Kodama proposed an invention similar to stereolithography, although no patent was filed at that time. The first patent related to SLA was later submitted by Chuck Hull in 1984, marking a milestone in the history of 3D printing. Hull proposed a device consisting of a laser directed onto a tank filled with photopolymer, intending to solidify successive layers of material until the desired part was formed. In this way, the process enabled the construction of an object layer by layer until the printing was completed (Agrawaal & Thompson 2021).

Hull's work opened the door to significant advances in 3D printing technology, leading to the development of different printing methods designed to enhance part quality and accelerate production. As a result, he became a pioneer in the fabrication of printers capable of producing parts with more complex designs and was also responsible for initiating the commercialization of 3D printers (Volpato 2021).

However, one of the greatest challenges at the time was the widespread adoption of 3D printing as a faster and simpler manufacturing method. Early printers were marketed at very high prices, which made them less attractive to both academia and industry. Over the following decades, new 3D printing techniques were developed and refined according to user needs and demands. Still in the 1980s, Carl Deckard developed the selective laser sintering (SLS) technology, based on the use of powdered materials. This approach offered major advantages, such as improved thermal properties and high resistance at elevated temperatures, which contributed to enhanced part finishing (Volpato 2021).

Over the years, various additive manufacturing techniques were established, including fused deposition modeling (FDM), created in 1988 by Scott Crump. Crump's patent led to the foundation of a company dedicated to the commercialization of FDM printers. With the method's popularization, different thermoplastic feedstocks were developed for this technique, which is based on the extrusion of molten material layer by layer onto the build platform. In recent years, FDM has become the most widely employed 3D printing method due to its low maintenance costs and ease of operation (Matias & Rao 2015).

By the 2000s, 3D printers began to be sold at more affordable prices. Despite this reduction, the cost remained high for several target groups. With the gradual dissemination of the technology, scientists started to develop new models and applications in medicine, civil engineering, the textile and food industries, and especially in academia, where 3D printing has been applied in the development of novel

laboratory instruments (Sharma et al. 2024, Cândido et al. 2024, dos Santos et al. 2022).

The technological progress in this field has been exponential, with new machines currently operating under the concept of 4D printing. In this approach, 3D printed materials are capable of changing their size and shape in response to external stimuli such as temperature, pressure, or humidity (Mehrpouya et al. 2021).

## Applications of Additive Manufacturing

Initially, additive manufacturing was conceived to increase the availability of parts for engineering purposes, mainly by reducing the overall time associated with fabrication, purchase, and delivery. Over time, the technology was refined into a rapid, relatively low-cost, and highly reproducible method, enabling its application in the healthcare sector for the development of prostheses, implants, hearing aids, and safety equipment. With these medical advances, biocompatible materials have been engineered, featuring improved mechanical properties, as well as injectable hydrogels designed to ensure structural integrity (Arefin et al. 2021, Bertsch et al. 2023).

Among the essential properties required for biomedical applications, flexibility is fundamental for prostheses to adapt to human physiology, while toughness is critical to ensure the material's ability to absorb energy and deform under impact without cracking (Hussan et al. 2024). Therefore, these materials must exhibit enhanced mechanical strength, greater similarity to biological tissues, and high biocompatibility, as they interact directly with joints, biological fluids, and the human body in general (Arefin et al. 2021).

Recent advances have also expanded the use of 3D printing into regenerative medicine. FDM has successfully fabricated PLA-based composites containing multifunctional bioactive glass to produce scaffolds (Bernardo et al. 2021).

Despite these advancements, additive manufacturing in biomedical applications has significant challenges. Depending on the type of additive manufacturing, the high roughness can promote bacterial adhesion, unreacted residual monomers, and diverse porosity in the device.

In civil engineering, additive manufacturing can drastically reduce the construction time of buildings. Traditionally, construction projects take several months to be completed; however, with the implementation of large-scale 3D printing machines, this period can be significantly shortened, while also reducing the need for manual labor (Ting et al. 2024, Praveena et al. 2022). Moreover, additive manufacturing has contributed to the development of industrial equipment, facilitating the replacement of automotive components and operational systems (Liu et al. 2021). However, scaling up additive manufacturing for structural applications introduces some bottlenecks, because on a large scale, this technology is limited when the topic is about concrete printing and controlling deposited layers.

In this context, engineering has increasingly focused on optimizing prototype development to minimize labor costs and streamline fabrication. This allows for the production of complex geometries and customized components directly tailored for industry. Robust parts that were once difficult to manufacture can now be fabricated using metals and other lightweight materials, thereby improving product performance.

The evolution of additive manufacturing has also enabled the production of components for aerospace and automotive applications, making these technologies more cost-accessible to companies. In addition, it promotes the use of lighter and easier-to-handle raw materials. Sustainable feedstocks can also be employed,

thereby contributing to waste reduction during fabrication (Liu et al. 2021). Additionally, the anisotropic mechanical properties of printed components pose a major challenge for safety-critical sectors, such as aerospace engineering, where strict regulatory standards require highly isotropic material behavior, a challenge that remains difficult to replicate consistently across different printing technologies.

The food industry began investing in 3D printing in the early 2000s, when a cake was designed using this technology, suggesting the feasibility of producing food while reducing waste of raw materials (Ligon et al. 2017). The aim is to simplify production, lower manufacturing costs, and create products similar to conventional ones already available on the market.

One of the main challenges for this sector is providing consumers with sensorially acceptable products while introducing innovation in flavors and structures. Sensory analysis commonly evaluates parameters such as texture, taste, aroma, and appearance. Nonetheless, 3D printing enables the development of personalized nutrition programs, particularly for individuals with food intolerances, as well as sophisticated projects in gastronomic design and customized cuisine (Ligon et al. 2017, Sharma et al. 2024).

The increasing use of edible biopolymers has further revolutionized this area, allowing for the fabrication of products such as chocolate, protein bars, purées, icings, edible gels, coatings, and doughs. Furthermore, 3D printing enables the production of vegan food products, such as cultivated meats, without the need for animal slaughter (Ligon et al. 2017).

In recent years, the textile industry has also embraced 3D printing to design anatomical clothing adapted to the human body, combining comfort, design, and innovation. For instance, the technology has been applied in the development of sports shoes designed to minimize impact during movement (Avinash et al. 2024).

Nevertheless, the textile sector is one of the most polluting industries worldwide, generating large amounts of waste that are often not reused. As an alternative, additive manufacturing has drawn attention for enabling the use of sustainable and unconventional raw materials, while also allowing for greater complexity in garment design without significantly increasing production costs (Khajavi 2021, Abisuga & de Beer 2023). One of the technical barriers for the textile industry is achieving strong adhesion between the extruded polymer and conventional textile substrates. Moreover, the low production throughput of current additive manufacturing technologies presents a major obstacle for high-volume mass production in the fashion industry.

Overall, 3D printing has become an important tool across multiple fields of research, especially in academia, where it contributes to the accelerated production of prototypes and supports continuous innovation in the creative process of new devices. The technology enables the development of complex designs and geometries that would otherwise be challenging to produce.

## PROTOTYPING AND MATERIALS

### Prototyping

Prototyping represents a fundamental stage in 3D printing, as it defines the process by which the object will be fabricated. At this stage, the complexity of the design is elaborated, and the initial visualization of the part is achieved. For multiple applications, prototypes can be produced in different colors for demonstrative, interactive, and aesthetic purposes, facilitating the presentation of the initial concept (Ligon et al. 2017). Therefore, prototyping is an essential process in additive manufacturing, especially

in the development of new devices through 3D modeling (Gabalski et al. 2023).

As previously mentioned, prototyping is carried out by preparing a digital model using appropriate 3D modeling software. Among the available CAD programs, there are both entry-level and advanced options. Table I presents examples of commonly used software for the design of different objects. Once the design is completed, the model is converted into the STL (Standard Triangle Language) format, which is the file type commonly recognized by slicing software.

Subsequently, the 3D representation is processed with slicing software that defines the printing parameters. For the FDM technique, these parameters include bed temperature, nozzle temperature, and printing speed. These settings are critical to ensure that the printed object is completed without defects. The slicing software converts the STL file into G-code, the machine-readable language containing the defined parameters as commands for the printer (Figure 1). After the object is printed, it may or may not undergo post-processing, aimed at removing burrs and imperfections. This stage may also involve the use of support structures, particularly in taller parts requiring physical reinforcement during printing (Kafle et al. 2021).

In addition to part fabrication, miniature systems can be fully modeled in 3D, contributing to reduced material costs, particularly metals, and minimizing physical space requirements. In this context, prototyping is one of the key stages of the creation process, as the design of the object plays a crucial role in determining the device's final configuration, enabling clearer, more precise visualization of the printed project (Li et al. 2018).

## Materials

Additive manufacturing is a versatile technique that allows the processing of a wide range of materials. Modelling can be performed using different feedstocks, which have been specifically developed to meet diverse application demands. As previously discussed, the techniques have been optimized to employ various precursors, such as thermoplastics, ceramics, thermosets, biomaterials, composites, and metallic alloys (Abisuga & de Beer 2023, Praveena et al. 2022).

Thermoplastics are among the most widely used materials due to their accessibility and relatively low cost. The most common examples include acrylonitrile butadiene styrene (ABS), polylactic acid (PLA), polypropylene (PP), and polyurethane (PU) (Alsabhi et al. 2023, Dadashi & Azadi 2022). Polymers such as PP and PU often require additional treatments and process optimizations due to their behavior during extrusion at high temperatures, which can lead to warping and shrinkage issues.

**Table I. Examples of software options for 3D modeling of parts and devices.**

| Software | Level | Cost |
|---|---|---|
| Tinkercad | Beginner | Free |
| SketchUp | Beginner | Free/Paid |
| Blender® | Intermediate | Free |
| Autodesk® | Intermediate | Free/Paid |
| AutoCAD® | Professional | Paid |
| SolidWorks® | Professional | Paid |

Therefore, careful control of filament diameter and surface quality is crucial to prevent issues during additive manufacturing. PLA, in contrast, offers significant advantages compared to other polymers, particularly its ability to yield high-resolution printed parts (Prasopdee et al. 2023). Furthermore, thermoplastics can be modified with conductive particles to fabricate sensors (Figure 2).

Metallic alloys and composites offer superior thermal resistance and can deliver improved surface finishing in the final printed object, despite the potential for structural defects. Their application, however, remains limited due to reduced flexibility and restricted prototyping options. In these cases, selective laser sintering (SLS) is typically employed for the fabrication of metallic objects (Wang et al. 2024). Another approach involves the deposition of metallic particles on the surface of a substrate or their incorporation into other materials to enhance properties and develop functional materials, particularly for applications in catalysis and sensing (Flores et al. 2022).

Ceramics are also extensively employed in additive manufacturing, where precise control of temperature and heating rate is critical to preserving material properties such as hardness. These materials are valued for their excellent mechanical strength, high resistance, corrosion toughness, and optical properties (Ligon et al. 2017).

Another important class of materials is biomaterials, which have gained considerable attention due to their versatile properties. Hydrogels and condensed biomaterials, for instance, exhibit superior mechanical strength and enhanced resistance to deformation

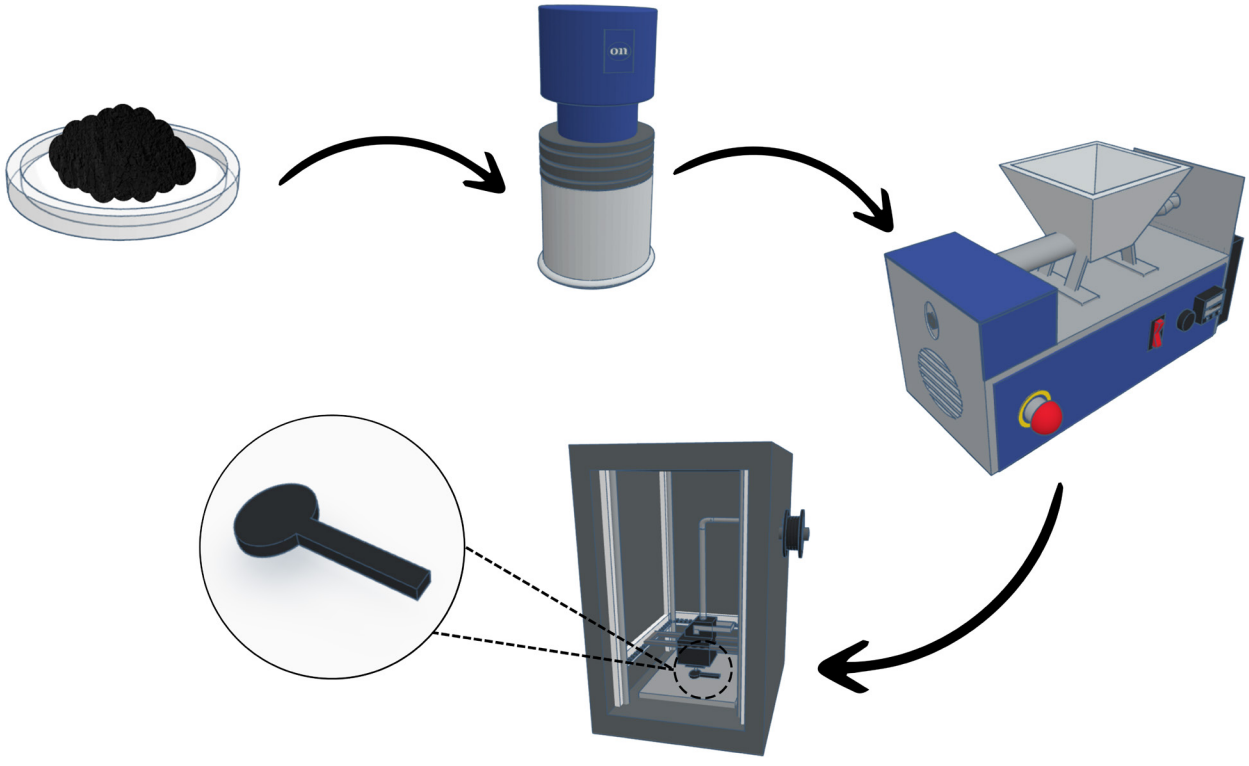


**Figure 1. Schematic representation of the prototyping and printing process: (1) design modeling using CAD software, (2) conversion of the file into .STL format for use in slicing software before printing, (3) conversion of the design into the machine-readable G-code language for fabrication, and (4) final printed object.**

compared to traditional biomaterials. In addition, they are biocompatible across different species and interact through dynamic bonding mechanisms (Bertsch et al. 2023).

Thus, prototyping and the use of different materials in additive manufacturing play a pivotal role in the development of novel equipment and devices, particularly sensors. A major advantage is the rapid production of functional sensors, often within a single day, using only appropriate design software. Traditionally, the fabrication of such devices required molds and complex shaping processes. Additive manufacturing, however, streamlines this process by reducing the number of steps involved in defining sensor geometries, while enabling the standardization of features such as length, thickness, flexibility, and stiffness.

## CONDUCTIVE FILAMENTS

The materials employed in the development of electrochemical sensors via additive manufacturing are diverse. Typically, the main precursors are thermoplastics such as PLA, ABS, TPU, among others. These filaments are composed of polymers combined with conductive particles such as graphene (G), carbon black (CB), graphite (Gr), and multi-walled carbon nanotubes (MWCNTs) (Ferreira et al. 2021). A major advantage compared to metallic materials commonly used for sensor fabrication is the lower production cost. All the materials were chosen according to the necessary or important intrinsic properties.

Carbon-based materials represent an advantageous alternative due to their reduced cost, making electrochemical sensors more accessible and commercially viable compared to metals. Moreover, these materials can be produced directly in the laboratory. Initially, polymers are blended with conductive particles and heated until a bulk composite is formed. This material is then ground and subsequently processed in an extruder.

The extrusion process consists of feeding the powdered material into a hopper with a screw mechanism that drives it toward a heated nozzle. The equipment must reach approximately 200 °C, depending on the polymer employed. The extruded filament acquires a cylindrical shape compatible with 3D printer feeding systems. A schematic representation of these steps is shown in Figure 3. The ability to produce tailored materials in the laboratory has enabled the combination of different carbonaceous fillers with a wide variety of polymers.

Among the most widely used carbon-based fillers, carbon black stands out for its spherical-like spatial arrangement, resulting from the high

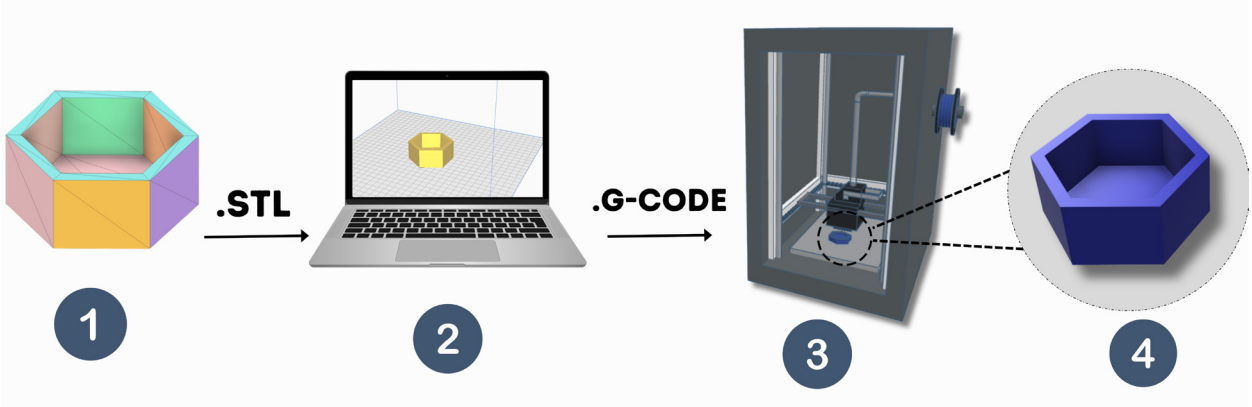



**Figure 2. Commonly used filaments for 3D printing, including commercial polymeric and conductive filaments**

concentration of carbon atoms interconnected by covalent bonds, which contribute to its relatively low cost and ease of incorporation into composite materials (Zheng et al. 2021). However, the electrochemical performance is often inferior to that of more structurally ordered carbon nanomaterials, in different applications requiring high sensitivity and fast electron transfer.

Graphene has attracted considerable attention due to its two-dimensional sheet-like structure in a hexagonal arrangement. Carbon atoms are covalently bonded, and one of their most notable features is their atomic-scale thickness. These present a particularly high mechanical strength and excellent charge carrier mobility (Zheng et al. 2021). Despite these advantages, implementation on a large scale is a challenge because of the reproducible synthesis and aggregation phenomena.

Graphite consists of multiple graphene sheets arranged in a planar stacking. These layers are held together by intermolecular Van der Waals interactions. A little trick is that a lower accessible surface area can limit electrochemical activity in sensing applications. Carbon nanotubes (CNTs) are cylindrical nanostructures composed of carbon atoms with diameters on the nanometer scale. They are recognized for their exceptional physical, electrical, and mechanical properties and are widely employed in nanotechnology, particularly in the fabrication of electrochemical sensors (Zheng et al. 2021). Nevertheless, their performance depends on structural parameters such as diameter and degree of functionalization, which can increase production costs.

Overall, the choice among carbon black, graphite, graphene, and CNTs involves a trade-off between cost, surface area, electrochemical

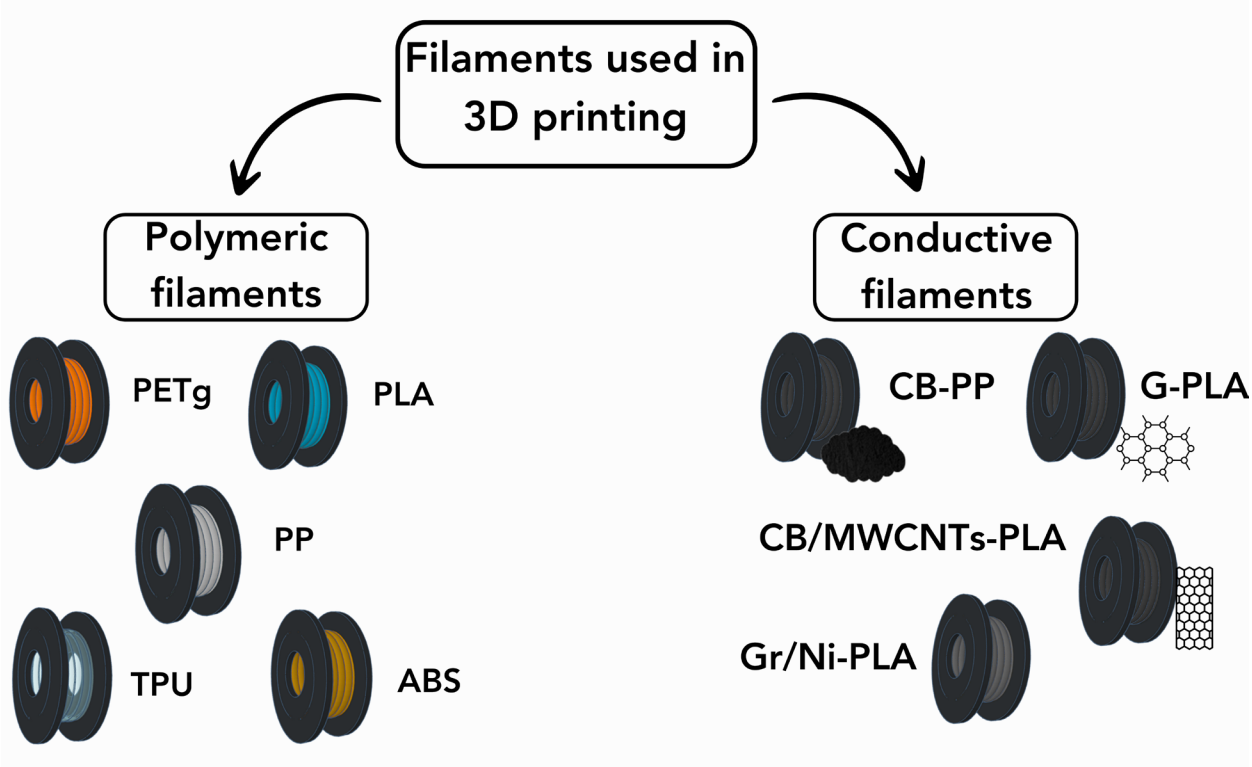



**Figure 3.** Schematic representation of conductive filament production for sensor fabrication via additive manufacturing

performance, and processability. The choice depends exclusively on cost and accessibility. Consequently, the material choice depends on the specific requirements of the intended sensing application and not a single intrinsic property.

Laboratory-produced filaments have gained relevance due to the possibility of incorporating conductive particles into different polymers. Carbon black and graphene, when combined with PLA, are frequently used in filament production, with the proportions adjustable to the desired properties without compromising the flexibility required for proper 3D printer processing (Stefano et al. 2022). Carbon black can also be combined with MWCNTs to fabricate sensors with larger surface areas and enhanced electrical conductivity (Crapnell et al. 2024).

PLA-based filaments can also undergo chemical treatment with dimethylformamide (DMF), which removes portions of the polymer matrix and exposes the conductive fillers on the surface. Characterization of these materials can be performed using techniques such as scanning electron microscopy (SEM) and X-ray diffraction (XRD) (da Silva et al. 2023). Thus, a wide variety of filaments can be engineered for application in electrochemical sensors aimed at detecting multiple species, using different types of thermoplastics.

Generally, a wide range of diverse conductive filaments has expanded all the possibilities for the development of electrochemical sensors. Nevertheless, improvements in conductivity, availability of surface area, and sensitivity must be carefully balanced against challenges related to reproducibility, cost, and manufacturing complexity.

Table II summarizes different filaments produced in the laboratory with a variety of conductive fillers, highlighting the advantages of carbon-based materials. These compounds offer clear benefits due to their relatively low cost compared to metallic counterparts and, additionally, can be combined with polymers that assist in filament structuring.

## 3D-PRINTED SENSORS

With technological advances, new strategies have emerged for developing analytical devices through additive manufacturing, driven by the lower production cost compared to other fabrication techniques and by the physical flexibility of the materials, which enables the production of lightweight and portable objects. Another advantage is the possibility of customizing these devices, which can be designed in advance for use in laboratory analyses and research development. Among the components produced are adapters, electrochemical cells, holders, and, most notably, sensors. Sensors are employed for detecting physical or chemical changes and act as transducers of different types of signals, most commonly electrical (Zhou et al. 2022).

Electrochemical sensors developed by 3D printing can be applied in several electrochemical applications. The most widely used 3D printing technique for fabricating these sensors is FDM, which employs a thermoplastic as the precursor material. Its advantages include low manufacturing cost, large-scale production of sensors, and straightforward equipment maintenance. On the other hand, one of the greatest challenges is ensuring that the sensors are reproducible and suitable for commercialization, or sufficiently reliable for accurate analyses (Pradela-Filho et al. 2024).

In recent years, the combination of additive manufacturing with electrochemical detection has rapidly evolved, particularly through the integration of conductive materials and microfluidic platforms, enabling the

**Table II. Conductive filaments produced with carbon-based fillers and thermoplastics.**

| Base Polymer | Conductive Material | Additives | Applications | References |
|---|---|---|---|---|
| PP | Carbon black | – | Pharmaceuticals and organic molecules | (Ramos et al. 2024) |
| PLA | Carbon black + MWCNTs | – | Pharmaceuticals | (Crapnell et al. 2024) |
| PLA | Carbon black | – | Organic molecules | (Stefano et al. 2022) |
| rPLA | Carbon black + Graphite | Castor oil | Biomarker | (Arantes et al. 2023) |
| PLA | Graphene | – | Biomarker | (da Silva et al. 2023) |
| rPETg | Carbon black + MWCNTs + Graphene | – | Biomarkers | (Camargo et al. 2024) |
| rPETg | Carbon black | Castor oil + microcrystalline cellulose | Neurotransmitter | (Ferreira et al. 2025) |
| PLA | Carbon black | Gold nanoparticles in castor oil | Neurotransmitter | (Bernalte et al. 2025) |
| PLA | Graphite | Kaolinite ($Al_2Si_2O_5(OH)_2$ | Biomarker | (Caldas et al. 2026) |
| PLA | Graphite | Nickel | Biomarker | (Caldas et al. 2025) |
| PLA | Carbon black | Babassu oil | Drugs | (Silva et al. 2024) |
| ABS | Graphite | – | Explosives | (Castro et al. 2024) |
| PLA | Graphite | Aluminum oxide ($Al_2O_3$) | Pharmaceuticals | (de Faria et al. 2024) |

**PP: Polypropylene; PLA: Polylactic acid; rPLA: Recycled polylactic acid; rPETg: Recycled poly (ethylene terephthalate glycol); ABS: Acrylonitrile butadiene styrene.**

development of compact and portable analytical devices (Selemani et al. 2024).

In addition to conventional FDM printers, other additive manufacturing approaches have been investigated for electrode fabrication. Some electrochemical sensors have also been fabricated using a 3D printing pen. To miniaturize additive manufacturing, the 3D printing pen functions as a mini-extruder, similar to FDM technology. However, the limitations of this process stem from the standardization and reproducibility of these electrodes (Lisboa et al. 2023).

To overcome all these limitations, it is essential to understand both the material properties and the stages of the additive manufacturing process, especially given the strong influence of the printer's mechanical variables, such as infill density, bed temperature, and nozzle temperature. Many researchers have devoted efforts to optimizing this system.

These sensors can be applied to detect different species and components in real

samples, such as urine, blood, water, and soil. They are therefore widely used in electroanalytical systems as a versatile tool, often providing high sensitivity in analysis (Silva et al. 2025).

In addition to electrochemical sensors, electrochemical cells can also be fabricated by FDM using a non-conductive polymer, aiming to promote the miniaturization of the electrochemical system. The main advantages of miniaturized electrochemical systems obtained by additive manufacturing include relatively low cost and the possibility of conducting in situ analyses (Henriques et al. 2025).

Both materials can be used to develop a 3D-printed-based flow device, with different microfluidic channels to support small liquid volumes, and, added to this, integrate both materials at the same printing to make this electrochemical device (Labuda et al. 2026).

As discussed earlier, electrodes produced by additive manufacturing with thermoplastics can undergo different post-printing treatments to expose conductive particles on the surface, increase the electroactive area, and improve the electrochemical response. Common procedures include exposing the materials to bases, acids, organic species, or plasma. Other methods have emerged as alternatives to the commonly used ones, for instance, the treatment of an electrochemical sensor with reactive oxygen cold plasma significantly improves the response due to the greater exposure of carbon black (Pereira et al. 2021).

However, chemical activation alone may not be sufficient to enhance the electrode surface response. In such cases, modification with metallic nanoparticles can be performed to improve electrocatalytic activity, thereby making the sensor more selective toward the detection of specific species (Teekayupak et al. 2023, Caldas et al. 2026).

Consequently, researchers have proposed innovations aimed at detecting organic species. Nanoparticles known as quantum dots can be deposited onto the electrode surface, increasing the electrochemical response area. Moreover, they show great potential for biosensor applications due to their biocompatible properties (Wan et al. 2023).

Table III summarizes the different electrodes fabricated for detecting chemical species in samples. These studies contribute to clinical analyses, environmental pollution monitoring, and contaminant identification. Electrochemical sensors can also be used for the simultaneous detection of chemical components, often present in complex mixtures. Thus, the development of 3D-printed sensors from lab-fabricated conductive filaments becomes feasible, given the use of relatively low-cost materials, ease of equipment handling during printing, and reduced fabrication time for multiple electrodes in a single day. Additional advantages of electroanalytical assays include lower energy consumption compared to other equipment, shorter analysis time, and reduced use of organic solvents.

## BIOSENSORS

Among electrochemical sensing platforms, biosensors have attracted considerable attention because they combine the inherent selectivity of biological recognition elements with the high sensitivity of electrochemical transducers. By incorporating biomolecules such as enzymes, antibodies, nucleic acids, or aptamers onto the electrode surface, biosensors enable the selective detection of a wide variety of clinically and environmentally relevant analytes (Silva et al. 2025, Cândido et al. 2024, Jiang et al. 2022).

3D printing is a technology that has become a key enabling tool in the development of

**Table III. Electrodes produced by additive manufacturing using conductive filaments for the detection of different analytes.**

| Electrode | Analyte | Linear range (μmol $L^{-1}$) | Limit of detection (μmol $L^{-1}$) | Refs. |
|---|---|---|---|---|
| CB/PP | Colchicine | 4.0 – 20.0 | 0.01 | (Ramos et al. 2024) |
| CB/MWCNTs/PLA | Paracetamol<br>Phenylephrine | 5.0 – 60.0<br>5.0 – 200.0 | 0.04<br>0.38 | (Crapnell et al. 2024) |
| CB/PLA | Catechol Hydroquinone | 0.5 – 60.0 1.0 – 50.0 | 0.02<br>0.22 | (Stefano et al. 2022) |
| CB/PLA | Ciprofloxacin | 1.0 – 12.5 | 0.30 | (Henriques et al. 2025) |
| CB/Gr/rPLA + castor oil | Oxalate | 10.0 – 500.0 | 5.70 | (Arantes et al. 2023) |
| G/PLA | Epinephrine | 4.0 – 100.0 | 0.20 | (da Silva et al. 2023) |
| G/PLA | Dopamine | 0.01 – 20.0 | 0.03 | (Wan et al. 2023) |
| CB/MWCNTs/G/rPETg | Uric acid Sodium nitrite | 30.0 – 500.0 0.1 – 5.0 | 0.27<br>2.69 | (Camargo et al. 2024) |
| CB/rPETg + castor oil and microcrystalline cellulose | Dopamine | 0.01 – 1.0 | 0.03 | (Ferreira et al. 2025) |
| Gr/Ni/PLA | Glucose | 50.0 – 1500.0 | 2.60 | (Caldas et al. 2025) |
| G/AgNPs/PLA | Rutina | 0.39 – 10.1 | 0.12 | (de Sousa et al. 2026) |
| G/ABS | Paracetamol | 0.20 – 30.0 | 0.054 | (Petroni et al. 2021) |
| CB/PLA + babassu oil | Cocaine | 5.0 – 200.0 | 1.20 | (Silva et al. 2024) |
| Gr/PLA | TNT RDX | 2.5 – 30.0 50.0 – 500.0 | 0.57<br>8.67 | (Siqueira et al. 2025) |
| Gr/$Al_2O_3$/PLA | Sulfamethoxazole | 2.0 – 40.0 | 0.40 | (de Faria et al. 2024) |

**CB/PP: carbon black and polypropylene; CB/MWCNTs/PLA: carbon black, multi-walled carbon nanotubes, and polylactic acid; CB/PLA: carbon black and polylactic acid; CB/Gr/rPLA: carbon black, graphite, and recycled polylactic acid; G/PLA: graphene and polylactic acid; CB/MWCNTs/G/rPETg: carbon black, multi-walled carbon nanotubes, graphene, and recycled polyethylene terephthalate glycol; CB/rPETg: carbon black and recycled polyethylene terephthalate glycol; Gr/Ni/PLA: graphite, nickel, and polylactic acid; G/AuNPs/PLA: graphite, silver nanoparticles and polylactic acid; G/ABS: graphite and acrylonitrile butadiene styrene; Gr/$Al_2O_3$/PLA: graphite, aluminum oxide, and polylactic acid; TNT: 2,4,6-trinitrotoluene; RDX: cyclotrimethylenetrinitramine.**

biosensors, as it was previously difficult to adapt them for *in situ* analysis due to their complexity. Moreover, additive manufacturing has made a significant contribution to the technological advancement of biosensors for the detection, diagnosis, and monitoring of diseases, viruses, and others (Kalligosfyri et al. 2026).

One of the greatest advantages of 3D-printed biosensors is the remarkable flexibility offered during device fabrication. This technology

enables the production of electrodes with customized geometries, integrated sensing platforms, and miniaturized analytical systems that would be difficult or prohibitively expensive to fabricate using traditional manufacturing techniques. In addition, additive manufacturing reduces material waste and fabrication time while facilitating the optimization of sensor architecture according to the intended analytical application.

The benefits of additive manufacturing extend beyond electrode fabrication. Recent developments have enabled the integration of complete electrochemical platforms, including sensing elements, microfluidic channels, sample reservoirs, electronic housings, and fluid management systems, into a single device. Such integration is particularly valuable for point-of-care (POC) diagnostics, where rapid analysis at the site of sample collection minimizes transportation requirements, reduces contamination risks, and provides faster clinical decision-making (Shi et al. 2025, Chan et al. 2017).

Furthermore, 3D printing has significantly advanced the development of lab-on-a-chip and organ-on-a-chip technologies by enabling the fabrication of sophisticated microfluidic architectures with high geometric precision. The capability to simultaneously manufacture structural components and analytical modules simplifies device assembly and reduces production costs, making integrated biosensing platforms increasingly accessible for both research laboratories and clinical applications (Raucci et al. 2026, Carvalho et al. 2021, Cook et al. 2025).

Another important advantage of 3D-printed biosensors is their rapid analytical response. Compared with conventional laboratory methods, which often require extensive sample preparation and prolonged analysis times, electrochemical biosensors can provide quantitative results within minutes while maintaining high analytical sensitivity. Consequently, these devices have become attractive alternatives for clinical diagnostics, disease screening, and continuous health monitoring.

Figure 4 shows a variety of applications using 3D-printing technology to develop different devices and to prototype auxiliary biosensing detection. In this way, the most important thing is facilitating the application of all the sensors in local detection, and 3D printing can be a good tool to assist and improve an increasing number of biosensors in direct applications. Complex, novel, and modern designs can be applied using this technique and may be more interesting for *in situ* analysis.

Additive manufacturing has significantly contributed to the development of these devices, particularly for detecting SARS-CoV-2-related and glucose-related biomarkers. During the pandemic, several research groups developed 3D-printed biosensors to enhance sensitivity in the identification of viral markers. Also, glucose monitoring remains a highly relevant field, since elevated blood levels can lead to the onset of diabetes and its associated complications.

Biosensors produced by 3D printing are generally fabricated from thermoplastic filaments combined with conductive particles. After printing, biomolecules are immobilized on the surface through different strategies, enabling direct application in biological samples such as plasma, urine, and saliva (Silva et al. 2025, Cardoso et al. 2020). Surface modifications are also explored, such as the incorporation of metal particles, especially gold, in order to improve the analytical response of electrochemical biosensors (Silva et al. 2022). This occurs because there is better interaction between the biomolecules and these metals.

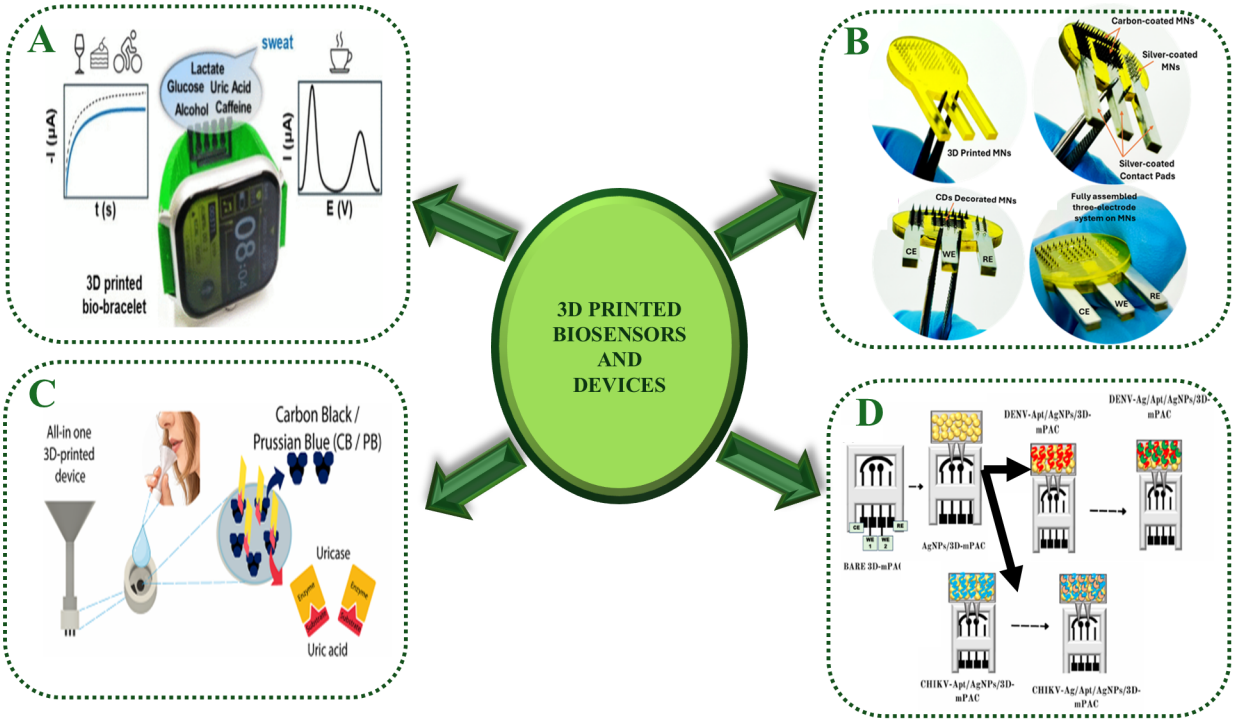



**Figure 4. Schematic representation of various 3D-printed devices and electrochemical biosensors for biosensing: (A) 3D-printed biometric electrochemical bracelet [Adapted with permission (Koukouviti et al. 2025). Copyright (2026), American Chemical Society], (B) conducting microneedle-based electrochemical biosensor [Adapted with permission (Kadian et al. 2025). Copyright (2026), Royal Society of Chemistry], (C) all-in-one 3D-printed device for uric acid detection [Adapted with permission (Raucci et al. 2026). Copyright (2026), American Chemical Society], and (D) portable device to put the paper-based modified sensor [Adapted with permission (Sharma et al. 2025). Copyright (2026), American Chemical Society].**

Thus, the availability of different polymers allows for customized systems that can assist in the interaction of these biomolecules, improving the performance of the biosensor. There are reports in the literature that electrodes based on thermoplastic polyurethane (TPU) can be modified with Prussian blue and carbon black nanoparticles, increasing the interaction with the target species (Gullo et al. 2025). This happens because the thermoplastic has a strong interaction with the other species, making the product perform better.

However, commercial graphene and PLA filaments, which are already commonly used in the fabrication of three-electrode systems, can undergo an electrochemical or chemical pretreatment process, exposing the conductive particles on the surface that will interact strongly with substrates to produce electrochemical biosensors. In this way, it favors the interaction with biomarkers of viral and neuropsychiatric diseases (Kalinke et al. 2021).

3D-printed electrodes can enhance sensitivity and even allow the simultaneous detection of nitrite and uric acid, enabling the analysis of multiple species within a single system (Cardoso et al. 2020). An indirect strategy is also possible, based on the immobilization of the enzyme glucose oxidase, which reacts with glucose to generate hydrogen peroxide as an electroactive byproduct (Wang & Pumera 2021).

Overall, the application of 3D printing in electroanalysis enables the development of diagnostic devices that are faster, more

affordable, and customizable. The design flexibility allows the fabrication of miniaturized systems tailored to different contexts, including resource-limited settings. Moreover, these biosensors can be applied to the monitoring of biomarkers associated with chronic and neurodegenerative diseases, such as Parkinson's disease, as well as in the evaluation of cholesterol and blood glucose levels (Kalinke et al. 2023b, Koukouviti & Kokkinos 2021, Calabria et al. 2023).

Another strategy explored to improve the performance of conductive filaments involves the incorporation of oils or plasticizing agents into the polymer matrix. These additives can enhance filament processability, flexibility, and the dispersion of conductive fillers, ultimately improving the electrochemical properties of the printed electrodes. An example is the work by (Sales da Rocha et al. 2026), who developed a conductive filament composed of graphite, castor oil, and polylactic acid (PLA). The resulting 3D-printed electrodes were employed to fabricate electrochemical sensing platforms, including a label-free immunosensor obtained through covalent immobilization of anti-clusterin antibodies on the electrode surface for the detection of the neurodegenerative biomarker clusterin. This study demonstrates that oil-based conductive filament formulations can serve as low-cost and versatile substrates for the development of electrochemical biosensors after appropriate surface modification.

Table IV summarizes examples of biosensors developed by additive manufacturing for the detection of biological species in real samples, highlighting the potential of these platforms in terms of wide linear ranges and low detection limits (LOD).

## OTHER SENSORS PRODUCED BY ADDITIVE MANUFACTURING FOR VARIOUS APPLICATIONS

### Pressure sensors

This class of sensors aims to measure any force applied to the surface of a piezoelectric material, generating an electrical current as a response (Jiang et al. 2022). They are highly relevant in healthcare applications, as well as in the automotive and aerospace industries. Their main advantages include the simplicity of preparation and low energy consumption (Gasperini et al. 2024, Hossain et al. 2024, Sanz-Pena et al. 2023).

The construction of these sensors can occur in two different ways: using conductive filaments with piezoelectric properties or by depositing material onto a piezoelectric substrate. In the first case, incorporating piezoelectric properties into the conductive material simplifies sensor fabrication by reducing substrate preparation steps (Kwon et al. 2021, Jin et al. 2025). In contrast, pressure sensors based on piezoelectric substrates with electrodes printed on their surface exhibit higher sensitivity (Sanz-Pena et al. 2023, Shahane et al. 2024).

Piezoelectric sensors can be applied to patients with diabetic foot syndrome through the insertion of optical waveguides into orthoses below the knee. These devices aim to assess the force exerted by the patient and, consequently, enable the development of prostheses with greater durability (Shahane et al. 2024). Moreover, the production of wearable sensors allows the integration of mechanical metamaterials for more versatile detection (Sanz-Pena et al. 2023). The incorporation of additional components into these devices enhances performance, broadens the range of measurable pressures, improves sensitivity, and maintains their relatively low production cost (Liu et al. 2020).

**Table IV. Biosensors produced by additive manufacturing using different conductive filaments.**

| Electrodes | Biological species analyzed | Technique | Linear range | LOD | Refs. |
|---|---|---|---|---|---|
| G/PLA/AuPs | Creatinine (SARS-CoV-2) | CV | 0.05 – 3.20 mmol $L^{-1}$ | 0.05 mmol $L^{-1}$ | (Silva et al. 2022) |
| CB/rPLA/PES/ COOH-MWCNT | YFV cDNA | SWV | 0.5 – 15 µmol $L^{-1}$ | 0.138 µmol $L^{-1}$ | (Kalinke et al. 2023a) |
| CB/PBNPs/TPU | Paraoxon | AMP | 2 – 20 ppb | 0.9 ppb | (Gullo et al. 2025) |
| G/PLA | PARK7/DJ-1 | CV | 5.0 – 500 µg $L^{-1}$ | 3.46 µg $L^{-1}$ | (Kalinke et al. 2023b) |
| CB/PLA CB/ABS | ChlOx ChOx | AMP | 30 – 240 µmol $L^{-1}$ 0.5 – 4.0 µmol $L^{-1}$ | 3.36 µmol $L^{-1}$ 0.08 µmol $L^{-1}$ | (Koukouviti & Kokkinos 2021) |
| CB/PLA | GOx | CV | 0.05 – 5.0 mmol $L^{-1}$ | 60 µmol $L^{-1}$ | (Calabria et al. 2023) |
| GNaOH/PLA | L-methionine | SWV | 5.0 – 3000 mmol $L^{-1}$ | 1.39 mmol $L^{-1}$ | (Kalinke et al. 2021) |
| G/PLA | Nitrite | AMP-BIA | 0.5 – 250 µmol $L^{-1}$ | 0.02 µmol $L^{-1}$ | (Cardoso et al. 2020) |
| G/PLA | Uric acid Glucose $H_2O_2$ Glucose | AMP | 0.5 – 250 µmol $L^{-1}$ 0 – 6.3 µmol $L^{-1}$ 50 – 500 µmol $L^{-1}$ 0.5 – 10 mmol $L^{-1}$ | 0.03 µmol $L^{-1}$ 15.0 µmol $L^{-1}$ 2.97 µmol $L^{-1}$ 473 µmol $L^{-1}$ | (Wang & Pumera 2021) |
| GR45CO15 | Clusterin | CV | 100 to 650 nmol $L^{-1}$ | 26.8 nmol $L^{-1}$ | (Sales da Rocha et al. 2026) |

**G/PLA/AuPs: graphene and polylactic acid with gold particles; CB/rPLA/PES/COOH-MWCNT: carbon black, recycled polylactic acid, polyethylene succinate, and carboxylated multi-walled carbon nanotubes; CB/PBNPs/TPU: carbon black–Prussian blue nanoparticles and thermoplastic polyurethane; G/PLA: graphene and polylactic acid; CB/PLA: carbon black and polylactic acid; CB/ABS: carbon black and acrylonitrile butadiene styrene; $G_{NaOH}$/PLA: graphene treated with sodium hydroxide and polylactic acid; YFV: yellow fever virus; PARK7/DJ-1: Parkinson's disease protein; ChlOx: cholesterol oxidase; ChOx: choline oxidase; GOx: glucose oxidase; $H_2O_2$: hydrogen peroxide; CV: cyclic voltammetry; DPV: differential pulse voltammetry; SWV: square wave voltammetry; AMP: chronoamperometry; AMP-BIA: chronoamperometry coupled to batch injection analysis system; GR45CO15: polylactic acid (PLA) with a conductive filler (graphite, GR) and a bio-based plasticizer (castor oil, CO) 45 % of GR and 15 % of CO.**

These sensors can be produced from different polymers using the FDM technique. Prototypes are initially designed in CAD software, printed, and subsequently subjected to resistance tests. Furthermore, studies have investigated the effect of thermal treatments, based on heating and cooling cycles, to improve device performance against temperature variations that could cause structural deformations. This process is essential to ensure greater sensor durability (Kwon et al. 2021).

Innovations in piezoelectric sensors are diverse, especially with the use of 3D printing as a production alternative. Many researchers are focused on developing more flexible and adaptable sensors, with emphasis on the detection of biological fluids and monitoring of human movements, aimed at advancing prosthesis development (Jin et al. 2025).

### Tactile skin sensors

Tactile skin sensors, also referred to as wearable sensors, mimic human skin by detecting variations such as temperature, deformations, and vibrations. One of the major challenges in this field is the development of slightly curvilinear sensors, since human skin does not present a completely flat surface. Technological advances have enabled the development of materials with greater flexibility and adaptability in this class of sensors. In this context, membranes and thin films can be produced through additive manufacturing for applications such as tactile skin sensors (Emon et al. 2022).

These sensors can be applied directly under the skin, provided they have sufficient mobility for adaptation and enhanced durability. Wearable sensors can be fabricated using different 3D printing techniques, such as DLP, and applied for temperature and contact force measurements, with the purpose of advancing robotics and improving force control in robotic interactions with surfaces (Wang et al. 2021).

Most tactile sensors have been developed for robotic applications, frequently in association with pressure sensors. Consequently, different materials have been investigated to enable the development of foldable sensors, artificial skins, and touch-sensitive surfaces, resembling the human sensory system (Zhou & Lee 2021).

3D printing is widely employed in this field due to its ability to produce complex and versatile prototype designs (Zhou & Lee 2021, Kalkal et al. 2021). The incorporation of metallic nanoparticles into wearable sensors, using silicone substrates, has even made it possible to measure arterial pulse, a goal that, until recently, might have been considered unfeasible (Lo et al. 2020).

### Temperature sensors

Many temperature sensors are designed for industrial applications, as thermal control is one of the greatest challenges in experiments affected by abrupt temperature variations. The development of temperature sensors capable of detecting small changes in specific locations has been facilitated by additive manufacturing. The response of these sensors can be evaluated through the thermoelectric effect. Highly conductive particles, such as carbon nanotubes, are commonly used as precursor materials, which can be doped with organic species to enhance sensitivity (Hwang et al. 2024).

These sensors may employ conductive particles applied either individually or in combination with insulating materials. Furthermore, multiple hybrid layers can be constructed depending on the intended application. In engineering, such sensors are essential, as they can respond based on electrical resistance or thermal variations in semiconductors. In many devices, conductive particles are incorporated to improve the response (Steckiewicz et al. 2021).

The base of these sensors can be fabricated via FDM using an insulating material. Areas with conductive pathways are strategically designed on the surface to maintain adequate conductive paths and ensure coherent resistance values. Nevertheless, it is necessary to preserve device flexibility, allowing application on curved surfaces (Steckiewicz et al. 2021).

Additionally, optical fiber sensors can be fabricated through DLP technology to simultaneously detect temperature and ultraviolet radiation, exhibiting high sensitivity in both responses (Chekkaramkodi et al. 2025).

### Humidity sensors

This class of sensors has broad applications in agriculture, environmental preservation, the development of sustainable packaging, and healthcare through wearable sensors. Their purpose is to detect variations or the presence of relative humidity in food samples, soil, wood, paper, human skin, and construction materials, thus preventing degradation over time (Lukacs et al. 2024, Pradela-Filho et al. 2024).

Ceramic materials offer the advantage of resistance to highly corrosive environments, which increases the durability of humidity sensors. Accordingly, such sensors can be produced by the DLP technique and sintered at different temperatures. However, these materials require strict porosity control, since porosity directly influences surface area (Milovanov et al. 2024).

Moreover, the production of comb-like electrodes becomes feasible by depositing conductive material onto thin films. When a liquid substance comes into contact with the electrodes, capacitance changes occur, which can be measured by a specific device (Lukacs et al. 2024).

Within the context of this review, it is worth emphasizing that additive manufacturing has wide application across different fields of knowledge, including engineering, chemistry, physics, agriculture, medicine, textiles, and food science. Technological progress has driven 3D printing toward the creation of complex models and accelerated the production of parts and devices. Furthermore, the technique has contributed to reducing manufacturing costs through material savings and decreased labor requirements. The development of novel designs has enabled the creation of sensors capable of detecting a wide variety of species.

Recently, additive manufacturing has gained ground in several strategic sectors, such as automotive, food, and medical industries, enabling the production of functional components with advanced geometries. The integration of computational tools further expands the possibilities for customization of devices, prostheses, and sensors. Advances in this technique have allowed the development of new materials with diverse applications. Figure 5 illustrates the different possibilities of 3D printing in areas such as medicine, engineering, food industry, and the development of new devices and electrochemical sensors.

## CONCLUSIONS AND PERSPECTIVES

Additive manufacturing has established itself as a versatile and transformative technology across industrial and academic settings due to its design flexibility, ease of customization, rapid prototyping, and cost-effective fabrication. In the field of electrochemical sensors and biosensors, 3D printing has enabled the development of customized conductive filaments, miniaturized sensing platforms, portable analytical devices, and integrated systems with complex geometries that would be difficult to achieve using conventional manufacturing techniques. These advances have expanded the possibilities for integrating functional materials with device architectures, accelerating the design and fabrication of next-generation sensing platforms.

Despite these significant advances, the electrical performance of currently available conductive filaments still generally falls short of that achieved with conventional electrode materials. In addition, several challenges continue to limit the widespread implementation of 3D-printed electrochemical devices, including the optimization of printing parameters, reproducibility between fabrication batches, surface activation procedures, and the lack of standardized manufacturing and

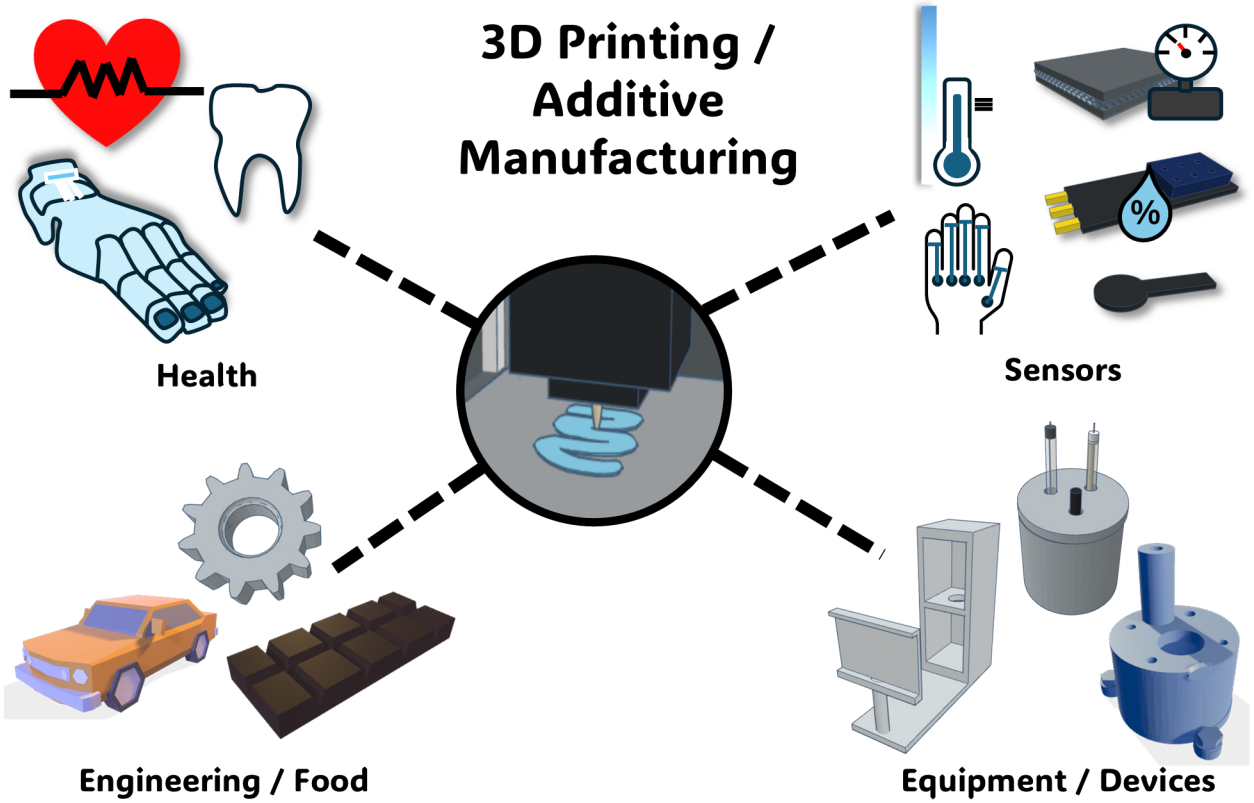



**Figure 5. Schematic representation of the different applications of 3D printing across various fields of knowledge and industry, including prostheses, automotive components, the food industry, as well as analytical devices and electrochemical sensors**

characterization protocols. These limitations hinder direct comparison among studies, reduce experimental reproducibility, and remain major obstacles to the translation of laboratory-scale prototypes into reliable commercial technologies.

Future research is expected to focus on the development of advanced conductive composites with improved electrical and mechanical properties, innovative surface functionalization strategies, and the integration of 3D-printed sensors with microfluidic platforms, wireless communication systems, flexible electronics, and Internet of Things (IoT) technologies for real-time and remote monitoring. At the same time, ensuring long-term stability, durability, analytical reliability, and user-friendly operation will be essential to facilitate the transition from proof-of-concept devices to practical applications.

Beyond conventional electrochemical sensing, recent advances demonstrate that 3D-printed biosensors are rapidly expanding into new application areas, including viral diagnostics, multimodal sensing, chiral analysis, direct-electron-transfer enzymatic biosensors, and bioelectronic interfaces capable of monitoring cellular and tissue activity with high spatiotemporal resolution. Examples include highly sensitive immunosensors and genosensors for SARS-CoV-2 detection, wearable biosensors for continuous health monitoring, smartphone-integrated analytical devices, and self-rolled three-dimensional biosensor arrays designed for electrophysiological recording from three-dimensional cell cultures and organoids.

These developments highlight the increasing convergence between additive manufacturing, advanced materials, electronics, and biomedical engineering.

Overall, the current evidence indicates that 3D-printed electrochemical sensors and biosensors are evolving toward multifunctional, wearable, implantable, multiplexed, and point-of-care analytical platforms capable of providing decentralized, real-time analysis in both clinical and environmental settings. Their ability to operate in resource-limited environments, where access to sophisticated laboratory infrastructure is restricted, represents one of their greatest advantages for expanding access to diagnostics and environmental monitoring. Although considerable progress has been achieved over the past decade, overcoming challenges related to material performance, device durability, large-scale manufacturing, reproducibility, and regulatory standardization will be crucial for enabling the successful commercialization and widespread adoption of these technologies.

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**ARIELLY CARDOSO**[1]
https://orcid.org/0009-0001-1422-5193

**JÉSSICA R. CAMARGO**[1]
https://orcid.org/0000-0003-1836-7495

**RODRIGO A.A. MUÑOZ**[2]
https://orcid.org/0000-0001-8230-5825

**BRUNO C. JANEGITZ**[1]
https://orcid.org/0000-0001-9707-9795

[1]Federal University of São Carlos, Laboratory of Sensors, Nanomedicine and Nanostructured Materials (LSNano), Anhanguera Highway, km 174, Rural Area, 13604-900 Araras, SP, Brazil

[2]Federal University of Uberlândia, Chemistry Institute, João Naves de Ávila Avenue, 2121, Block 1D, Santa Mônica Campus, 38400-902 Uberlândia, MG, Brazil

Correspondence to: **Bruno Campos Janegitz**
*E-mail: brunocj@ufscar.br*

## Author contributions

Arielly Cardoso: Conceptualization, literature review, writing – original draft; Jéssica R. Camargo: Literature review, writing – review and editing, data organization; Rodrigo A. A. Muñoz: Critical revision of the manuscript and editing; Bruno C. Janegitz: Supervision, project administration, funding acquisition, critical revision of the manuscript and editing.

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**Data availability**

Data sharing does not apply to this article as no new data were created or analyzed in this study. All data supporting this review are available in the cited literature.

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