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ARTICLE

Systematic analysis of deposition modules in 3D bioprinting

Análisis sistemático de los módulos de deposición en bioimpresión 3D

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Abstract

3D bioprinting requires deposition modules capable of transforming bioinks into reproducible, viable, and stable structures. This study presents a systematic review of scientific literature and patent documents related to deposition modules used in extrusion-based, inkjet, and laser-assisted bioprinting techniques. The methodology followed PRISMA guidelines adapted for technological analysis and included literature searches, document selection based on predefined criteria, and a patentometric analysis of patent applications and granted patents published between 2021 and 2025. Patentometric Representativeness (PR), defined as the proportion of patents associated with each technique relative to the total number of patents analysed, was used to identify innovation trends across different bioprinting technologies. In addition, the Deposition Error Index (DEI) was proposed as a technical metric to estimate the percentage deviation between the deposited dimension and the target dimension, thereby assessing the potential technical performance of deposition modules. The final sample included 32 patents: 18 related to extrusion-based bioprinting, 4 to inkjet bioprinting, and 10 to laser-assisted bioprinting. The PR analysis indicated the predominance of extrusion-based systems (56.3%), followed by laser-assisted bioprinting (31.3%) and inkjet technology (12.5%). The results show that recent innovation is focused on modular systems, coaxial nozzles, detachable printheads, ultrasound-assisted and magnetic field-assisted deposition, as well as hybrid bioprinting platforms. It can be concluded that the design of deposition modules should be evaluated not only in terms of resolution and cell compatibility, but also with respect to modularity, sterilization capability, inline monitoring and control, geometric fidelity, and integration with automatic feedback mechanisms.

Index terms: 3D bioprinting, deposition modules, extrusion bioprinting, inkjet bioprinting, laser-assisted bioprinting, patentometric analysis, deposition error index (DEI), geometric fidelity, printhead.

Resumen

La bioimpresión 3D requiere que el módulo de deposición convierta la biotinta en estructuras reproducibles, viables y estables. Este trabajo presenta una revisión sistemática de literatura científica y patentes sobre módulos de deposición en técnicas de extrusión, inyección de tinta (inkjet) y bioimpresión asistida por láser. La metodología siguió los lineamientos PRISMA adaptados al análisis tecnológico. Incluyó búsqueda bibliográfica, selección según criterios definidos y análisis patentométrico de solicitudes y concesiones publicadas entre 2021 y 2025. Se utilizó la representatividad patentométrica (RP), que mide la proporción de patentes de cada técnica respecto del total, para identificar innovaciones por tipo de bioimpresión. Además, se propuso el Índice de Error de Deposición (IED), que calcula la desviación porcentual entre la dimensión depositada y la dimensión objetivo para evaluar el potencial técnico del módulo. La muestra final incluyó 32 patentes: 18 de extrusión, 4 de inkjet y 10 de láser. La RP indicó un predominio de la extrusión (56.3%), seguida de la bioimpresión asistida por láser (31.3%) y la tecnología inkjet (12.5%). Los resultados muestran que la innovación reciente se centra en sistemas modulares, boquillas coaxiales, cabezales desmontables, asistencia por ultrasonido o campo magnético y plataformas híbridas. Se puede concluir, que el diseño de módulos de deposición debe evaluarse no solo por su resolución o compatibilidad celular, sino también por su modularidad, esterilización, control en línea, fidelidad geométrica e integración con mecanismos de retroalimentación automática.

Palabras clave: bioimpresión 3D, módulos de deposición, extrusión, inkjet, láser, patentometría, error de deposición, fidelidad geométrica.

I. INTRODUCTION

Within the field of tissue engineering, bioprinting has emerged as a technology capable of fabricating customized tissue scaffolds using biomaterials that can be deposited through a computer-controlled system at specific locations within a defined three-dimensional space [1], [2], [3]. Its primary application lies in regenerative medicine. Unlike conventional 3D printing, bioprinting must simultaneously balance geometric accuracy, biomaterial integrity, and cell viability.

Cell viability refers to the ability of cells to remain alive and functional [4]. This aspect is particularly relevant in bioprinting because the biomaterials, or bioinks, used to fabricate functional tissues are subjected to shear stress during the deposition process. Consequently, cell viability becomes a critical factor in ensuring the proliferation and differentiation of biocompatible tissues.

In this context, the balance maintained by the bioprinting system determines how the material is dispensed, the magnitude of the mechanical stress applied to the cells contained within the bioinks, the resolution achievable by the system, the stability of the deposited filament or droplet—depending on the printing technique employed—and, ultimately, compatibility with sterilization procedures and process control requirements.

The most widely used deposition techniques—extrusion-based, inkjet, and laser-assisted bioprinting—present distinct advantages and limitations. Extrusion bioprinting enables the use of higher-viscosity bioinks and the fabrication of larger-scale structures; however, it may induce shear stress within the filament where cells are embedded and requires precise synchronization among pressure, flow rate, and printhead movement [5], [6]. Inkjet bioprinting, in contrast, offers high-speed droplet deposition with low material consumption. Nevertheless, its performance depends on the rheological operating window of the bioink, droplet stability, and the prevention of nozzle clogging [7], [8]. Laser-assisted bioprinting allows material deposition without direct contact through a nozzle, significantly reducing the risk of mechanical contamination and clogging. However, this technology generally involves greater optical complexity, higher costs, and stricter alignment requirements [9].

To compare these technologies, patentometric representativeness (PR) was incorporated as a metric. This indicator uses the total number of patents included in the analysis and the number corresponding to each bioprinting technique to assess the technological prominence of each system and the relative concentration of inventive activity surrounding each type of deposition module.

Although patentometric representativeness enables the technological comparison described above, it does not directly evaluate the technical performance of deposition modules. Therefore, its interpretation can be complemented by indicators such as the Deposition Error Index (DEI), defined as the percentage deviation between the deposited geometric dimension and the target dimension specified in the design [10], [11]. This metric can be adapted to each bioprinting technique: in extrusion bioprinting, through filament width or diameter and pore area; in inkjet bioprinting, through droplet diameter, volume, or spacing; and in laser-assisted bioprinting, through positional accuracy or transferred area. While patentometric representativeness describes technological advancement reflected in patent documents, the DEI establishes a connection between inventive activity and functional design criteria such as accuracy, repeatability, deposition stability, and defect control.

The objective of this study was to systematically review scientific literature and patent documents related to deposition modules in 3D bioprinting, with particular emphasis on extrusion-based, inkjet, and laser-assisted bioprinting techniques. Specifically, the study sought to identify temporal trends, leading countries and applicants, recurring design criteria, and opportunities for improvement in the development of more robust, modular, and adaptable deposition modules capable of accommodating different bioinks and biomedical applications.

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II. METHODOLOGY

A. Research Design

The present study was conducted through a systematic review of patent documents and scientific literature focused on bioprinting deposition modules, with particular emphasis on extrusion-based, inkjet, and laser-assisted bioprinting systems. The methodological process was structured according to PRISMA principles and criteria adapted for technological and engineering analyses, with the objective of comparing deposition systems, identifying key design criteria, and recognizing the advantages, limitations, and emerging trends associated with each bioprinting technique.

The search strategy was divided into two main stages. First, patent documents were collected and screened. Second, a scientific literature search was conducted to contextualize and support the technological findings identified during the first stage. In both cases, Boolean operators and technical terms related to bioprinting—such as bioprinting, printhead, deposition module, nozzle, extrusion, laser, and inkjet—were employed to obtain precise and relevant search results.

B. Literature Search

The search for scientific articles was conducted using high-impact academic databases. The general search query was defined as follows:

("3D bioprinting" OR bioprinting OR biofabrication) AND ("deposition module" OR extrusion OR printhead OR nozzle OR dispenser OR inkjet OR syringe)

The search query was subsequently adapted for each bioprinting technique; therefore, separate search strategies were developed for extrusion-based, inkjet, and laser-assisted bioprinting. Publications written in English and Spanish were considered, with no restrictions regarding country of origin, provided they were published between 2016 and 2025. Documents focused exclusively on conventional 3D printing or on biomedical applications that did not describe the deposition subsystem with sufficient technical detail were excluded from the review.

C. Patent Search and Selection

The technological search was conducted using the patent databases Google Patents, WIPO PATENTSCOPE, Espacenet, and The Lens. Keyword combinations adapted to patent terminology were employed; for example:

(bioprinter OR bioprinting) AND (extrusion OR printhead OR dispensing system OR nozzle OR syringe mechanism)

Published patent applications, granted patents, and patent families related to the design or operation of bioprinting modules exclusively applied to 3D bioprinting were included in the analysis. The patentometric study period was limited to 2021–2025. Additionally, the CPC classification code B33Y was used as an additional filtering criterion during the screening process.

The retrieved records were organized into independent databases according to bioprinting technique, duplicate entries were removed, and a manual relevance assessment was performed through the review of titles, abstracts, and available technical content.

D. Inclusion and Exclusion Criteria

The inclusion criteria for patent documents were as follows: (i) patents related to extrusion-based, inkjet, or laser-assisted bioprinting; (ii) publication between 2021 and 2025; and (iii) explicit descriptions of deposition modules, printheads, nozzles, or dispensing systems.

Patents related to conventional 3D printing without bioprinting applications, documents published prior to 2021, and records lacking a clear description of the deposition module were excluded from the analysis.

For the scientific literature, original research articles and review papers published between 2016 and 2025 were included if they focused on bioprinting or deposition systems and provided information regarding modules, printheads, dispensing mechanisms, or technical, mechanical, and biological performance parameters.

Conference abstracts without full-text availability and studies lacking sufficient technical information on the deposition subsystem were excluded from the review.

E. Analysis variables and evaluation metrics

From each patent document, relevant general, technological, and operational data and variables were extracted. General variables included publication year, applicant country or jurisdiction, document type, and associated bioprinting technique. On the other hand, the technological variables included the type of deposition module, actuation mechanism, printhead architecture, nozzle configuration, modularity, multimaterial capability, ease of sterilization, and the possibility of integration with control or feedback systems. Finally, the operational variables included working pressure, deposition speed, nozzle diameter, resolution, temperature, compatible viscosity range, accuracy, repeatability, cell compatibility, and risk of clogging.

As the primary patentometric metric, Patentometric Representativeness (PR) was used and calculated for each technique using the following expression (1):

From each patent document, relevant general, technological, and operational data and variables were extracted. General variables included publication year, applicant country or jurisdiction, document type, and associated bioprinting technique. On the other hand, the technological variables included the type of deposition module, actuation mechanism, printhead architecture, nozzle configuration, modularity, multimaterial capability, ease of sterilization, and the possibility of integration with control or feedback systems. Finally, the operational variables included working pressure, deposition speed, nozzle diameter, resolution, temperature, compatible viscosity range, accuracy, repeatability, cell compatibility, and risk of clogging.

As the primary patentometric metric, Patentometric Representativeness (PR) was used and calculated for each technique using the following expression (1):

$$PR_i = \left(\frac{n_i}{N}\right) x\ 100 \qquad (1)$$

Where PR_i corresponds to the patentometric representativeness of technique i, n_i represents the number of patents selected for that technique, and N corresponds to the total number of patents included in the final sample. In this study,

$N = 32$ patents. This metric allowed the comparison of the relative concentration of patenting activity among extrusion, inkjet, and laser-assisted bioprinting technologies, without assuming that a greater number of patents necessarily implies superior technical performance.

To complement PR from a different perspective, the Deposition Error Index (DEI) was incorporated as a proposed technical metric. DEI is defined as the percentage deviation between a deposited geometric dimension and the target dimension specified in the design. Its general expression is:

$$DEI_i = \left(\frac{\left| G_{real,i} - G_{design,i} \right|}{G_{design,i}} \right) x\ 100 \qquad (2)$$

Where $G_{real,i}$ corresponds to the actual dimension obtained after deposition and $G_{design,i}$ corresponds to the target dimension defined in the model, pattern, or programmed trajectory. Depending on the technique being evaluated, this dimension may correspond to filament width or diameter in extrusion bioprinting, droplet diameter, volume, or spacing in inkjet bioprinting, or transfer position, area, or diameter in laser-assisted bioprinting.

The DEI makes it possible to relate the design of the deposition module to its geometric performance. According to its definition, lower values indicate higher deposition fidelity, reflecting greater process stability and reduced deviation from the intended design. Consequently, while PR is used to interpret patent-driven innovation, DEI evaluates deposition accuracy, repeatability, filament or droplet stability, clogging control, and overall deposition quality. By combining both metrics, deposition modules can be analysed from both technological and technical perspectives, enabling a more comprehensive assessment of system performance.

III. Results

A. Document Selection

Following the patent screening process, 32 patents related to deposition modules in 3D bioprinting were selected [12], [13], [14], [15], [16], [17], [18], [19], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43]. The final sample consisted of 18 patents associated with extrusion-based bioprinting, 4 patents related to inkjet bioprinting, and 10 patents corresponding to laser-assisted bioprinting. The selection process confirmed that the vast majority of the documents retrieved prior to screening were related to conventional three-dimensional printing, biomaterials, biological applications, or other components of bioprinters that were not relevant to the scope of this study.

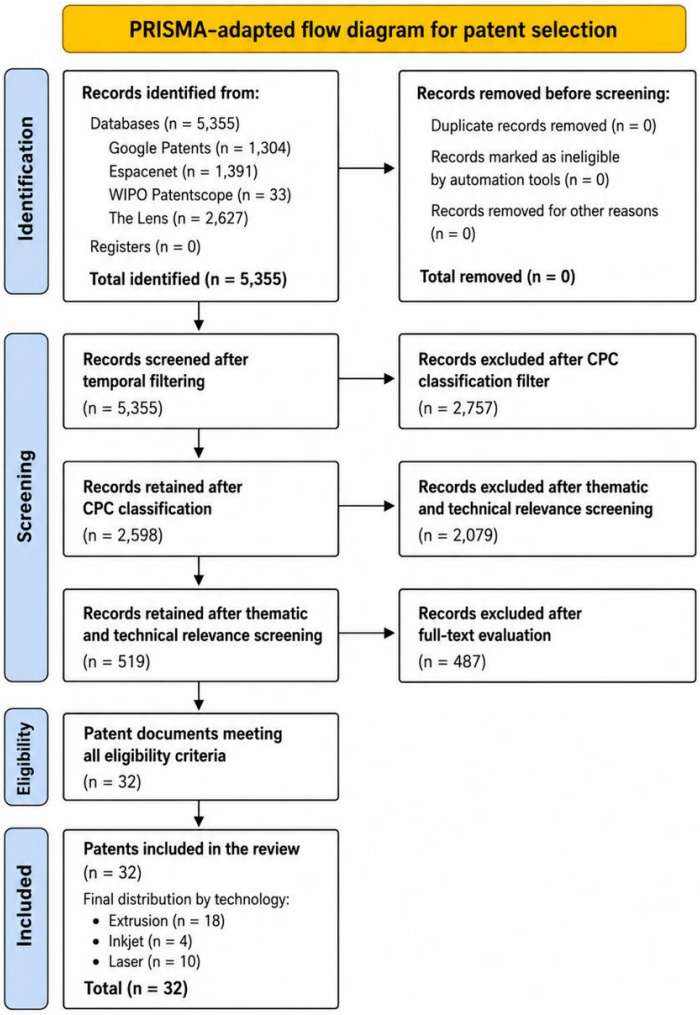

Fig. 1. Flowchart corresponding to the Identification of studies via databases and registers.

TABLE 1
SELECTED PATENTS FOR EACH TECHNIQUE

Bioprinting Technique	Selected Patents (n_i)
Extrusion	18
Inkjet	4
Laser assisted	10

PR was used to analyze the distribution of patenting activity among the selected technologies, whereas DEI was incorporated as a technical metric associated with the expected precision of deposition modules when experimental data regarding deposited geometries are available.

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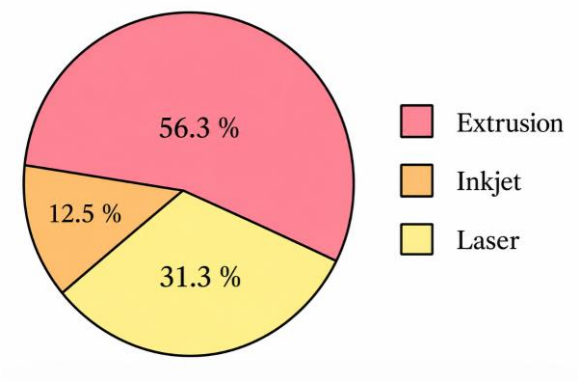

Fig. 2. Patentometric Representativeness by Bioprinting Technique.

B. Patent Activity Trends

According to the temporal distribution, extrusion-based bioprinting exhibited the most intensive patenting activity, with a marked increase between 2022 and 2024 within the selected sample. In contrast, inkjet bioprinting showed a more limited presence, with patent publications distributed across the period from 2022 to 2025. Finally, laser-assisted bioprinting displayed a more evenly distributed level of activity, with relative increases observed between 2021 and 2024. The 2025 data should be interpreted with caution, as the year may not have been complete at the time of the patent search and data collection process.

TABLE 2
SELECTED PATENTS BY YEAR AND BIOPRINTING TECHNIQUE

Technique	2021	2022	2023	2024	2025
Extrusion	0	2	5	9	2
Inkjet	0	1	1	1	1
Laser	3	1	1	3	2

C. Geographic Distribution and Applicants

Regarding extrusion-based bioprinting, the records included in the sample are primarily concentrated in China and in international patent documents, such as WO applications. This suggests a combination of local academic and technological development alongside international intellectual property protection strategies. For inkjet bioprinting, the sample is predominantly concentrated in the United States, with applicants associated with additive manufacturing and biofabrication platforms. Finally, for laser-assisted bioprinting, the geographic distribution includes the United States, China, and European Patent Office (EP) filings, reflecting a more diverse patenting landscape and broader international participation in the development of this technology.

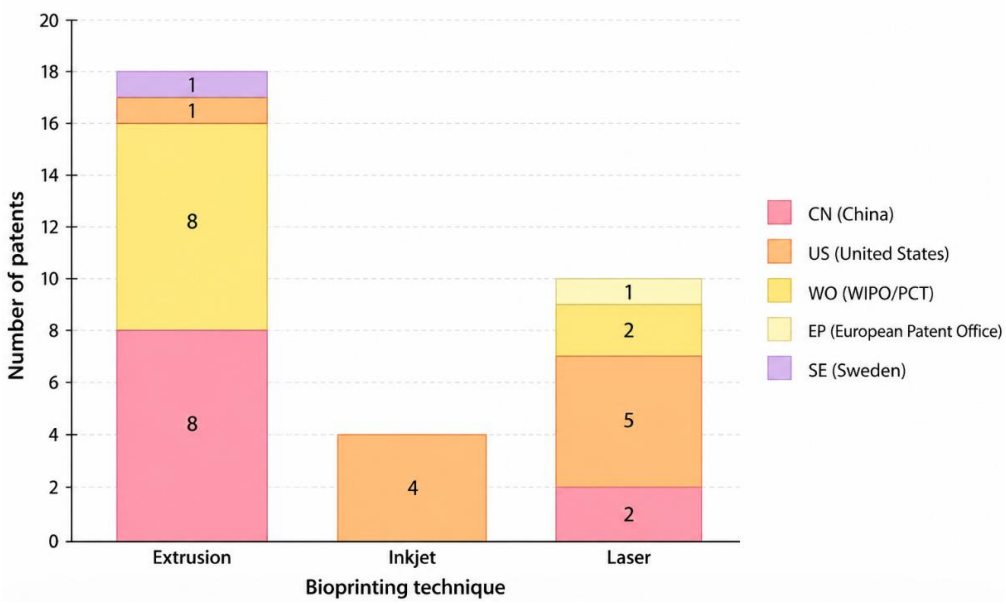

Fig. 3. Patent Distribution by Jurisdiction and Bioprinting Techniques.

D. Emerging Technological Trends

The review of patent titles and descriptions indicates that innovation in extrusion-based bioprinting is primarily focused on detachable printheads, coaxial nozzles, multi-nozzle pneumatic systems, ultrasound-assisted extrusion, photocuring coupling, and magnetic field-assisted deposition. These solutions aim to improve filament stability, expand bioink compatibility, reduce assembly times, and enable multilayer or multimaterial architectures. From the perspective of the DEI, these improvements represent strategies for reducing deviations in filament width, layer height, trajectory continuity, and pore area.

In inkjet bioprinting, the selected patent documents address the printing of three-dimensional structures, multimaterial filaments, and droplet-based assembly processes. The lower PR associated with this technique does not indicate technological irrelevance, but rather a more limited application domain due to viscosity requirements, droplet formation constraints, and clogging control challenges. Nevertheless, inkjet bioprinting maintains significant potential for high-resolution cellular patterning, low-volume assays, and manufacturing processes with reduced biomaterial consumption. In this technique, the DEI is associated with errors in droplet diameter, ejected volume, droplet spacing, and the presence of satellite droplets.

For laser-assisted bioprinting, the reviewed patents include cellular printing systems, laser-induced transfer devices, biological component printing technologies, and multitechnology platforms. The observed patent activity reflects strong interest in contactless deposition, precise cell transfer, and the reduction of limitations associated with nozzle-based systems. However, optical system complexity and implementation costs remain important barriers. In this case, the DEI can be estimated from transfer positioning errors, deposited area measurements, or the deviation between the programmed cellular pattern and the resulting deposited pattern.

E. Design Criteria by Bioprinting Technique

To complement Patentometric Representativeness (PR) with a functional interpretation of deposition module design, the design criteria identified in the selected patent documents were synthesized and analyzed. This classification enables the assessment not only of the number of documents associated with each bioprinting technique, but also of the predominant engineering approaches, deposition module actuation mechanisms, degree of modularity, expected precision, and their potential relationship with the Deposition Error Index (DEI).

TABLE 3
DESIGN CRITERIA IDENTIFIED IN EXTRUSION BIOPRINTING PATENTS

Design Axis	Representative Patents	Main Technical Approach	Implication for the Deposition Module	Relationship with DEI
Syringe–Actuator Interface	US 2023/0264417 A1	Syringe adapter and extrusion system	Improves compatibility among cartridges, actuator, and printhead	May reduce flow-rate variations and filament-width errors
Integrated Microfluidics	WO 2023/026099 A1	Fiber formation through microfluidic channels	Controls mixing, focusing, and gelation before extrusion	Promotes more uniform filaments and lower dimensional deviation
Detachable Coaxial Printhead	CN113290858B	Core–shell deposition with removable printhead	Facilitates cleaning, sterilization, and multilayer configurations	Reduces errors caused by clogging, misalignment, or cross-contamination
Optimized Coaxial Nozzle	SE 2250804 A1; WO 2024/005697 A1	Fixed or modular coaxial geometry	Improves concentricity, flow stability, and nozzle reconfiguration	Reduces deviations in diameter, wall thickness, or core–shell geometry
Multi-Nozzle Architecture	CN114536760A; CN117901405A	Multiple pneumatic or ultrasound-assisted nozzles	Enables multimaterial printing and increased productivity	Requires control of registration errors between materials and nozzles
Advanced Robotics and Motion	WO 2024/077032 A1	Robotic bioprinting system	Expands trajectories, degrees of freedom, and adaptation to complex surfaces	DEI depends on synchronization between trajectory and flow rate
Detachable Printhead	WO 2024/098119 A1	Interchangeable modular printhead	Reduces maintenance time and facilitates bioink or technique changes	Improves repeatability if reassembly preserves alignment and sealing
Clinical Portability	WO 2023/244197 A1; WO2025083309A1	Handheld or intracorporeal device	Brings extrusion technology into surgical or in situ contexts	May increase operator-dependent error but improves clinical applicability
Thermal Management	CN217098932U	High-temperature pneumatic nozzle with rapid assembly	Improves flow of viscous or thermoprocessable materials	May reduce clogging but requires control of thermal damage to cells
Bioactive Integration	WO 2024/228814 A2	Electroporation integrated into the printhead	The printhead not only deposits material but also functionally modifies cells	Performance depends not only on geometric error but also on viability and functional patterning

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Design Axis	Representative Patents	Main Technical Approach	Implication for the Deposition Module	Relationship with DEI
Ultrasound Assistance	CN118789811A; CN117901405A	Ultrasound-assisted extrusion	Reduces friction, adhesion, and nozzle clogging	May reduce errors caused by irregular flow or partial obstruction
Coupled Photocuring	CN119141869A	In situ extrusion and optical solidification	Stabilizes soft hydrogels during deposition	Reduces post-deposition deformation and improves geometric fidelity
Auxiliary Magnetic Field	CN120003032A	Extrusion with magnetic-field-induced orientation	Allows organization of the internal bioink microstructure	DEI should be complemented with orientation or functional anisotropy metrics

TABLE 4
DESIGN CRITERIA IDENTIFIED IN INKJET BIOPRINTING PATENTS

Design Axis	Representative Patents	Main Technical Approach	Implication for the Deposition Module	Relationship with DEI
Discrete Droplet Deposition	US 12441050 B2; US 11738501 B2	Additive manufacturing of 3D structures using microdroplets	Enables precise dispensing of small volumes and defined patterns	DEI can be measured through droplet diameter, volume, and position
Digital Pattern Control	US 12441050 B2; US 11738501 B2	Programmed droplet placement layer by layer	Improves repeatability, XY resolution, and material efficiency	Reduces deviations between designed and deposited patterns
Multimaterial Printhead	US 12005631 B2	Oriented, twisted, or helical multimaterial filaments	Enables programmable internal architecture and material orientation	DEI should consider not only external geometry but also internal orientation
Droplet-by-Droplet Assembly	US 11213797 B2	Construction of structures using droplets as functional units	Promotes compartmentalized cellular microenvironments	Error can be evaluated through droplet spacing, coalescence, and local fidelity
Precise Microdispensing	US 11213797 B2; US 12441050 B2	Piezoelectric, thermal, or microvalve actuation	Controls ejection volume, frequency, and velocity	Reduces volumetric variability between deposition events
Rheological Compatibility	US 12441050 B2; US 11738501 B2	Use of fluids with appropriate viscosity and surface tension	The bioink operating window determines droplet stability	DEI increases in the presence of satellite droplets, trajectory deviation, or clogging
High Resolution and Low Consumption	US 11213797 B2; US 12005631 B2	Deposition of microvolumes for fine patterns	Suitable for microarchitectures, cellular assays, and localized dosing	Promotes fidelity at the microscale, although it limits large volumetric constructs

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TABLE 5
DESIGN CRITERIA IDENTIFIED IN LASER ASSISTED BIOPRINTING PATENTS

Design Axis	Representative Patents	Main Technical Approach	Implication for the Deposition Module	Relationship with DEI
Contactless Transfer	US 11045996 B2; US 11707881 B2	Laser printing of biological components	Avoids direct mechanical contact and eliminates nozzle clogging	DEI is associated with transfer position, deposited area, and spot size
High Cell Density	US12331272B1; WO2025194541A1	Transfer of ultra-high-density multicellular tissues	Promotes constructs with greater cell–cell interaction	Performance should be evaluated together with cell density and tissue integrity
Single-Cell Printing	CN113021874A	Annular laser spot-induced transfer	Enables extremely precise individual cell positioning	DEI can be measured as cell-to-target positional error
Multi-Technology Platform	US 2024/0359498 A1	Integration of more than one printing modality	Combines the advantages of extrusion, inkjet, and laser technologies in a single architecture	DEI should be evaluated by modality and synchronization between printheads
Integrated Modular Platform	WO 2024/167956 A1	Bioprinter and related components	Reinforces the concept of a complete technological ecosystem	Improves repeatability if subsystems maintain stable calibration
Instrumental Optimization	US 11707881 B2	Physical device for biological laser printing	Improves optical alignment, stability, and repeatability	Reduces variability caused by misalignment, donor–substrate distance, or spot size
Material–Process Compatibility	EP 4442767 A2; US 11407168 B2	Printing of P4HB and copolymers	Adjusts process conditions to specific biomaterials	DEI should be complemented with mechanical properties, degradation behavior, and biocompatibility
Clinical Portability	CN-116214921-A	Laser-assisted biological gun	Brings laser technology to localized or clinical applications	May increase manual variability but improves access and in situ applicability

F. Technical Interpretation Using the Deposition Error Index (DEI)

Although the DEI could not be experimentally determined for the complete patent dataset due to the limited availability of dimensional data and the absence of standardized measurement protocols within patent documents, its proposed use as an indicator establishes a connection between the inventive activity reflected in patents and the expected functional performance of deposition modules. This metric could be implemented in future studies through microscopic image

analysis, computer vision techniques, geometric characterization of filaments or droplets, and the evaluation of deviations between digital designs and fabricated structures.

Following this rationale, an extrusion module with a low PR but a low DEI could still be considered technically competitive, whereas a technique with a high PR but a high DEI would require improvements in process control. Therefore, the combined use of PR and DEI makes it possible to distinguish between the concentration of patent-related innovation and actual deposition performance, thereby avoiding the interpretation of patent quantity as a direct substitute for precision or geometric quality.

IV. Discussion

The incorporation of design criteria into the research makes it possible to broaden the interpretation of Patentometric Representativeness (PR), since a greater number of patents does not necessarily imply technical superiority, but rather a higher concentration of inventive activity around specific engineering problems in the clinical or practical aspects of bioprinting. In relation to the above, PR should be used together with different functional variables such as modularity, precision, repeatability, rheological compatibility, ease of sterilization, integration with inline control, and reduction of deposition error.

Extrusion exhibited the highest PR within the sample, which may be explained by its versatility in processing medium- and high-viscosity bioinks, its compatibility with volumetric constructs, and the possibility of integrating multiple actuation mechanisms. However, the analysis of the design criteria shows that this technique also concentrates a great diversity of technical problems that have not been completely solved. The reviewed patents not only seek to improve basic syringe-based extrusion, but also to optimize the actuator–cartridge interface, stabilize flow through microfluidics, incorporate coaxial nozzles, facilitate printhead replacement, integrate multiple nozzles, and add physical assistance through ultrasound, photocuring, electroporation, or magnetic fields. Therefore, although extrusion is a mature technology in terms of adoption, it is still active in innovation due to common challenges such as clogging, filament variability, shear stress applied to cells, cleaning, sterilization, and synchronization between flow rate and movement.

From the perspective of the Deposition Error Index (DEI), extrusion is linked to the relationship between pressure, flow rate, travel speed, nozzle diameter, bioink viscosity, and post-deposition stability. Therefore, coaxial, detachable, ultrasound-assisted, or photocuring-coupled designs may be interpreted as strategies to reduce possible geometric deviations, improve filament uniformity, and maintain tissue shape after deposition. However, each improvement introduces new calibration requirements; that is, multi-nozzle systems require registration control between materials, coaxial systems depend on concentric alignment, thermal or optical systems must balance fluidity or solidification with cell viability, and finally, portable or intracorporeal platforms face greater variability in manual operation or clinical restrictions.

In the case of inkjet technology, PR was lower, but the design criteria show a more specific technical orientation toward volumetric precision, discrete deposition, and microstructural control. The selected patents focus on controlled droplet generation, layer-by-layer fabrication of three-dimensional structures, microdroplet assembly, and printheads capable of generating multimaterial filaments with internal orientation. The above indicates that inkjet technology does not necessarily compete with extrusion technology in terms of volume or compatibility with different types of viscous bioinks, but rather in applications where low-consumption microvolumes, high resolution, and well-defined cellular patterns are required. In other words, its value is less associated with building large scaffolds and more with fabricating microarchitectures, cellular microenvironments, and precise dosing systems.

With respect to DEI in inkjet technology, it should be evaluated through variables such as droplet diameter, ejected volume, droplet spacing, impact position, coalescence, the presence of satellite droplets, and repeatability between ejection events. For this reason, the design of the deposition module depends strongly on the rheological window of the bioink, surface tension, ejection frequency, actuation mechanism, and the distance between the nozzle and the substrate. Although this technique offers high precision, its main limitation remains its sensitivity to clogging and to formulations with high viscosity. Consequently, the lower PR of inkjet technology should not be interpreted as low relevance, but rather as an indication of a specialized technology conditioned by chemically strict requirements.

Laser-assisted bioprinting exhibited an intermediate PR; however, the design criteria reveal an orientation toward high-precision applications, contactless transfer, individual cell positioning, dense tissue printing, and hybrid platforms. In contrast to extrusion and inkjet techniques, laser-assisted bioprinting reduces or eliminates problems associated with direct nozzle contact, such as clogging, mechanical contamination, and friction on the material. This makes it especially attractive for applications where spatial control and cell preservation justify greater instrumental complexity.

In terms of DEI, laser technology should be evaluated through transfer positioning error, spot size, deposited area, donor–substrate distance, applied energy, and the repeatability of each pulse. In the case of single-cell printing, the error may be measured as the deviation between the target position and the actual position of each deposited cell. In high-cell-density systems, geometric fidelity should be complemented with biological criteria such as cell density, viability, tissue integrity, and multicellular organization. Therefore, although laser bioprinting may offer very high precision, its main barriers are cost, optical calibration, maintenance complexity, possible thermal or energy-related stress, and scalability for large constructs.

The overall comparison of design criteria suggests that the three techniques should not be understood as mutually exclusive alternatives, but rather as technological pathways with highly complementary strengths. Extrusion can provide compatibility with viscous bioinks, modularity, scalability, and multimaterial capability; inkjet technology contributes precise dosing, low consumption, and droplet-by-droplet control; whereas laser-assisted bioprinting provides contactless deposition, high spatial resolution, and reduced clogging. Taken together, the characteristics and advantages mentioned above support a trend toward hybrid, reconfigurable, and intelligent modules capable of integrating interchangeable printheads, sensors, trajectory control, physical assistance, and automatic feedback.

The design criteria tables strengthen the discussion because they allow a transition from a purely quantitative reading of patents to an engineering interpretation of the deposition module. Thus, PR identifies where patenting activity is concentrated, while DEI and functional criteria make it possible to analyze which technical problems are being addressed. This combination makes the evaluation more robust because it avoids assuming that the technique with the greatest number of patents is necessarily the best, and allows each technology to be assessed according to its potential performance, operational limitations, and biomedical applicability.

V. Design criteria proposal for a deposition module

Based on the findings of this review, it is proposed that the design of a deposition module for 3D bioprinting should consider the following minimum criteria:

- Modular and detachable architecture to facilitate cleaning, sterilization, maintenance, and switching between deposition techniques.

- Compatibility with a wide range of bioink viscosities through interchangeable cartridges, nozzles, or printheads.
- Synchronized control of pressure, flow rate, applied energy, and movement speed to stabilize filament width, droplet size, transfer position, or deposition area.
- Integration of sensors or inline vision systems to detect clogging, geometric variations, trajectory deviations, satellite droplets, and deposition defects.
- Design strategies aimed at minimizing mechanical stress on cells and preserving cell viability throughout the printing process.
- Evaluation of the Deposition Error Index (DEI) through the measurement of filaments, droplets, transferred areas, or positional deviations relative to the programmed design.
- Integration with photocuring, ultrasound-assisted, magnetic field-assisted, or multimaterial deposition strategies when required by the intended application.

VI. Conclusions

The systematic and patentometric review made it possible to identify that recent innovation in deposition modules for 3D bioprinting is mainly concentrated in extrusion systems, followed by laser-assisted and inkjet technologies. The Patentometric Representativeness (PR) metric showed a distribution of 56.3% for extrusion, 31.3% for laser-assisted bioprinting, and 12.5% for inkjet within the final sample of 32 patents. However, these values should not be interpreted as a direct measure of technical superiority, but rather as an indicator of the relative concentration of inventive activity surrounding each technology.

On the other hand, the incorporation of design criteria made it possible to complement PR with a functional interpretation of each technique. In extrusion bioprinting, the patents reveal a trend toward more versatile, detachable, coaxial, multimaterial modules assisted by physical stimuli such as ultrasound, photocuring, electroporation, or magnetic fields. Regarding inkjet technology, although its patentometric representativeness was lower, the design criteria show a clear orientation toward volumetric precision, digital droplet control, microarchitectures, and, above all, low biomaterial consumption. Finally, in laser-assisted bioprinting, the analyzed documents reflect a trend toward contactless transfer, high-precision cell positioning, printing of high-cell-density tissues, hybrid platforms, and portable devices. This technology reduces problems associated with nozzles and enables high spatial resolution, although it faces significant barriers related to cost, optical calibration, instrumental complexity, and scalability.

The Deposition Error Index (DEI) is proposed as a complementary technical metric to relate deposition module design to its functional performance. In extrusion bioprinting, it can be applied to filament width or diameter; in inkjet bioprinting, to droplet diameter, volume, or spacing; and in laser-assisted bioprinting, to transfer position, area, or size. Its use together with PR could make it possible to analyze technologies not only according to their presence in patent documents, but also according to their potential ability to produce reproducible, accurate, and geometrically stable structures. However, this study is limited by the information available in the databases consulted and by the time period defined for the patentometric review. Likewise, DEI was proposed as a complementary technical metric, but it was not experimentally calculated for all patents due to the lack of homogeneous data regarding deposited dimensions, measurement protocols, and printing conditions. Therefore, future research should incorporate multicriteria evaluation approaches, patent family analyses, patent citation studies, and experimental validation of representative modules

through direct measurements of deposition error. Such integration would make it possible to relate inventive activity more accurately to the actual performance of deposition modules in 3D bioprinting.

In conclusion, the obtained results support the development of hybrid, modular, and inline-controlled deposition modules capable of combining the material compatibility of extrusion, the volumetric precision of inkjet technology, and the contactless deposition capabilities of laser-assisted bioprinting. The future of deposition module design appears to be oriented toward reconfigurable platforms with interchangeable printheads, sensor integration, multiphysics assistance, and automatic feedback mechanisms aimed at reducing defects, improving repeatability, and expanding the biomedical applicability of 3D bioprinting.

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