MALAYSIAN JOURNAL OF MICROSCOPY

Journal homepage: https://malaysianjournalofmicroscopy.org

REVIEW ARTICLE

A BIBLIOMETRIC ANALYSIS OF 3D PRINTING FOR BONE TISSUE REGENERATION

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Abstract. 3D printing technology in tissue regeneration discipline played a pivot role in the sustainable growth of human healthcare. Publication based on 3D printing and tissue regeneration discipline has exhibited an exponential growth due to the vast expansion of the research output. In regard to current publications, the authors investigated the trends regarding 3D printing technology in tissue regeneration discipline, focusing on bone. An analysis using the keywords "3D printing" and "bone tissue regeneration" revealed that 261 papers were published between 2015 and 2024. The number of publications on these topics increased significantly, raising from 2 in 2015 to 70 in 2024. The materials extrusion, directed energy deposition, powder bed fusion, materials jetting, and photopolymerization were currently the most often types of technology used to produce 3D biomedical products related to bone tissue regeneration. Meanwhile, metal, polymer, ceramic, composite, smart material, and special material were the most frequently used materials as matrix or filler in biomedical 3D printing technology. Studies in the current literature reveal that composites are favored due to material properties that can be customized to meet specific requirements including mechanical strength, heat resistance, flexibility, and chemical resistance. The Chinese government has strategically invested in regenerative medicine and 3D bioprinting to address healthcare challenges and position the nation at the forefront of medical innovation. As for method, fused deposition modeling (FDM) is frequently chosen among researchers due to cost-effectiveness, user-friendly and compatibility to wide range of thermoplastic materials. This review will provide significant support by offering scientific insights to assist future research in the field of tissue regeneration.

Keywords: 3D printing, bone tissue regeneration, scaffold, extrusion, composite.

Article Info

Received 24 February 2025
Accepted 3 October 2025
Published 4 December 2025

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ISSN: 1823-7010, eISSN: 2600-7444

1. INTRODUCTION

3D printing technology has made significant advancements, particularly in the tissue regeneration discipline, transforming diverse perspective of healthcare and medical research at present [1]. One of the most remarkable applications of 3D printing in tissue regeneration is bioprinting, where living cells are deposited sequentially in layers with bioinks to create functional tissues and even organs [2]. This technology holds immense potential for organ transplantation, as it could mitigate the shortfall in donor organs [3]. Thousands of patients worldwide die each year while waiting for compatible organs [4]. Traditional organ donation is limited by several factors, including donor availability, immunological compatibility, and ethical concerns. In response to this crisis, researchers have been exploring innovative solutions, with 3D bioprinting emerging as a promising technology to address the issue.

3D printing also enables the creation of personalized implants and prosthetic, leading to better patient outcomes. In addition, 3D printing allows for the fabrication of complicated drug delivery systems, including personalized pills with specific dosages and release profiles [5]. This technology enables precise controls over drug administration, enhancing therapeutic efficacy while minimizing side effects. Moreover, researchers utilize 3D printing to create custom laboratory equipment, microfluid devices, and tissue scaffolds in investigating disease, drug testing, and regenerative medicine applications [6-8]. This flexibility accelerates research and innovation in the biomedical discipline.

Ongoing advancements in 3D printing materials expand the range of biomaterials available for the biomedical applications. These materials include biocompatible polymers, ceramics, and even bioinks containing living cells for bioprinting. Over the past decade, there has been a consistent upward trajectory in publications concerning 3D printing technology for tissue regeneration research, indicating a global surge in interest on the subject (Figure 1). The most prevalent types of 3D printing technology, including material extrusion, directed energy deposition, powder bed fusion, materials jetting, and vat photopolymerization [9]. This paper will focus on 3D printing technology for bone tissue regeneration. Analysis of the Scopus database reveals a significant increase in publications related to "3D printing", and "bone tissue regeneration" from 2015 to 2024 (Figure 2). In addition, the data of types of 3D printing technology presented on the same figure show that in 2024, extrusion (30 publications) has the most significant increase in publication followed by energy deposition (10 publications).

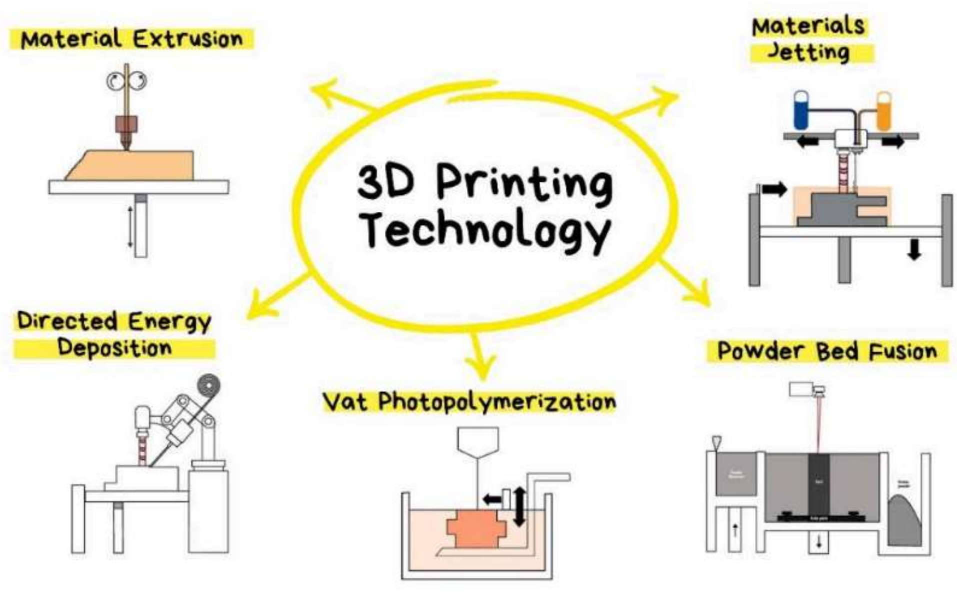

Figure 1: Current trend of biomedical 3D printing technology

The data from Figure 2 highlights the ongoing development and increasing interest in research within the field "3D printing" and "bone tissue regeneration" which continues to attract attention from scientists and the academic community. Among the materials discussed for 3D printing technology in bone tissue regeneration are metals (excellent physical properties), polymers (low cost and processing flexibility), ceramics (durable and fire resistant), composites (exceptional versatility and tailorable properties), smart materials (alterable by external condition e.g. heat and water) and special materials (e.g. textile and food) [10]. Despite the compatibility of various materials with 3D printing technology in bone tissue regeneration, this study focuses specifically on the abovementioned materials. Analysis of publications in the Scopus database revealed a decrease in the number of articles when keywords were combined. Specifically, a search combining "3D printing, bone tissue regeneration, metals, polymers, ceramics, composites, smart materials, and special materials" yielded result as in Table 1.

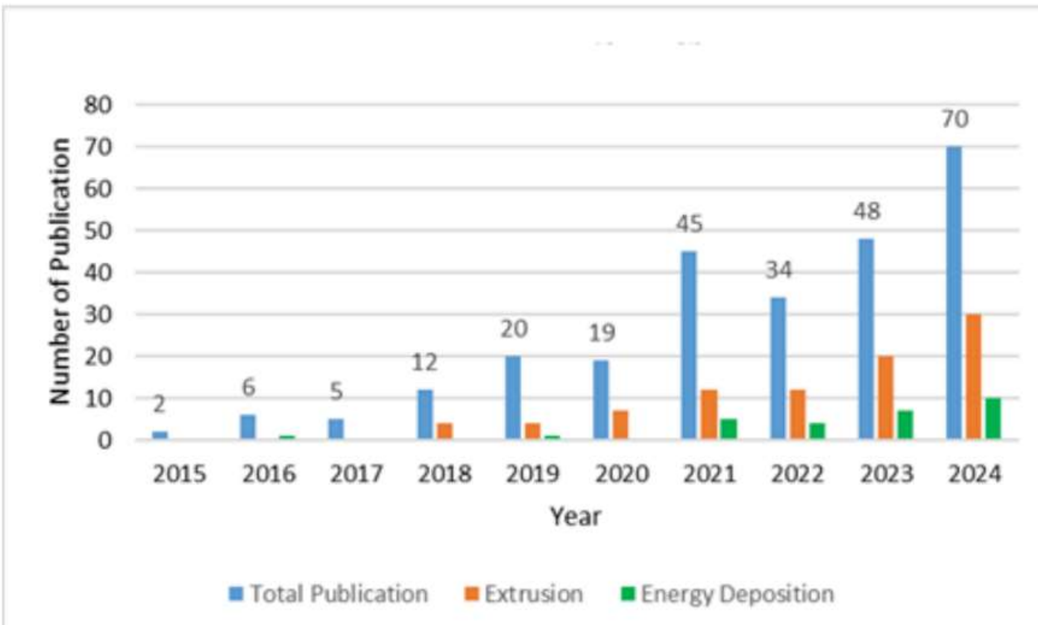

Figure 2: Number of publication using keywords "3D Printing" and "Bone Tissue Regeneration" in Scopus database (2015-2024)

Table 1: Published articles using keywords 3d printing, bone tissue regeneration, metal, polymer, ceramic, composite, smart material, and special material

Keywords	Publication (2015-2024)
3d printing + bone tissue regeneration	261
3d printing + bone tissue regeneration + metal	76
3d printing + bone tissue regeneration + ceramic	171
3d printing + bone tissue regeneration + polymer	218
3d printing + bone tissue regeneration + composite	233
3d printing + bone tissue regeneration + smart material	42
3d printing + bone tissue regeneration + special material	16

Natural bone is an intricate composite primarily composed of organic matrix (mainly collagen) and inorganic mineral phase such as hydroxyapatite. To replicate this composition, researchers have developed composite materials that combine biopolymers with inorganic components. For instance, composites made of inorganic phases like nanosilicate particles, calcium phosphate, and bioactive glasses integrated with biopolymer matrices have been investigated as building blocks for bone constructs [11,12]. This combination captures elements of bone's physiological structure, enhancing the bioactivity and mechanical properties of the engineered scaffolds. The integration of inorganic materials such as hydroxyapatite or tricalcium phosphate into polymer matrices significantly enhances the mechanical strength and osteoconductivity of the scaffolds. These composites exhibit improved mechanical properties, making them more suitable for load-bearing applications in bone tissue engineering. Additionally, the presence of bioactive ceramics promotes better integration with the host bone tissue, facilitating the bone healing process. The combination of organic and inorganic components in composite materials results in synergistic effects that enhance the overall performance of the scaffolds. Both constituents contribute to the composite's bioactivity, cohesivity, and rheological properties, leading to improved cell attachment, proliferation, and differentiation. This synergy is crucial for the successful integration and functionality of the engineered bone tissue.

Most of the publications discusses composite (233 publications) as material used for 3D printing technology in bone tissue regeneration. Ceramic-polymer composite combines the advantages of both polymer and ceramic materials which are essential for bone tissue regeneration. Polymers are favoured in 3D printing processes due to several key reasons. Polymers offer an extensive range of material properties that can be customized to meet specific requirements, such as mechanical strength, flexibility, heat resistance, and chemical resistance. This versatility allows for the creation of composite materials with diverse characteristics to suit various applications. Polymers are generally easier to process compared to other materials like metals or ceramics. They can be melted and extruded or cured sequentially in layers during the 3D printing process, making them suitable for additive manufacturing techniques. This ease of processing enables complex geometries to be fabricated with relative simplicity. Polymers are often more cost-effective than other materials, making them an attractive choice for 3D printing applications, especially when producing prototypes or low-volume parts. The availability of a wide range of polymer materials at varying price points further enhances their cost-effectiveness. Many polymers used in 3D printing, such as certain types of thermoplastics, are biocompatible and safe for use with the biological tissues or fluids. This renders polymers appropriate for applications in the bone tissue regeneration. The main purpose of this study is to systematically evaluate the impact, trends, and patterns of 3D printing for bone tissue regeneration. It involves the quantitative assessment of academic publications, citations, and authorship networks to identify influential studies, emerging topics, and key contributors. Bibliometric analysis helps researchers and policymakers understand the evolution of scientific knowledge, assess research productivity, and make informed decisions regarding future studies and funding priorities.

2. BONE TISSUE REGENERATION IN 3D PRINTING TECHNOLOGY

A number of research were issued discussing the 3D printing technology for bone tissue regeneration particularly using materials extrusion, directed energy deposition, powder bed fusion, materials jetting, and vat photopolymerization.

2.1 Materials Extrusion

Material extrusion or filament deposition process, also known as fused deposition modelling (FDM), is a widely used 3D printing process in the bone tissue regeneration due to its versatility, cost-effectiveness, and proficiency in multiple materials types [13]. 3D printing for bone tissue regeneration using materials extrusion typically involves selecting a biocompatible polymer suitable for the application. Common material includes polylactic acid (PLA), polyethylene glycol (PEG), polycaprolactone (PCL), and various thermoplastic elastomers. These materials are chosen based on factors such as biocompatibility, mechanical properties, and sterilization compatibility. The selected polymer filament is loaded into the 3D printer's extruder system, where it is heated to its melting point for extrusion. The material is feeds through a preheated nozzle with a specific diameter, where it is deposited layer by layer onto build platform or previous layer, once molten. The 3D model is sliced into thin horizontal layer using specialized software, which generates toolpath for the extruder to follow.

2.2 Directed Energy Deposition

Directed Energy Deposition (DED) is an additive manufacturing process used in 3D printing for bone tissue regeneration, particularly for fabricating large, complex, and high-performance metal components. DED typically utilizes metal powders as the feedstock material [14]. Common biomedical-grade metals include titanium alloys, stainless steel, cobalt-chromium alloys, and nickel-titanium alloys. These materials are selected based on their biocompatibility, mechanical properties, and suitability for medical implants. In DED, metal powder is delivered to the deposition area through a nozzle or powder delivery system. The powder may be delivered coaxially or laterally to the energy source, depending on the setup of the 3D printer. DED employs a high-energy source, typically a laser or an electron beam, to melt and fuse the metal powder onto the substrate or previously deposited layers [15]. The energy source is precisely controlled and directed using mirrors or electromagnetic coils to achieve accurate deposition. The energy source selectively melts and metal powder at specific locations according to the toolpath generated by the slicing software.

2.3 Powder Bed Fusion

Powder Bed Fusion (PBF) is one of the additive manufacturing techniques used in bone tissue regeneration for fabricating metal and polymer parts with high precision and intricate geometries. PBF can utilize a variety of materials, including metals such as stainless steel, alloys, and polymers like polyamide (nylon), polylactic acid (PLA), or polyether ether ketone (PEEK) [16]. Material selection depends on factors such as biocompatibility, mechanical properties, and intended application in biomedical devices and implants. The process begins with the preparation of a thin layer of fine metal or polymer powder spread evenly across the build platform inside the 3D printer. This powder layer serves as the raw material for the fabrication process. PBF involves selectively melting or sintering the powdered material in specific areas to form the desired 3D geometry. This is typically achieved using high-energy source, such as laser or an electron beam, which is precisely controlled according to the 3D model's design. The energy source selectively heats the powder bed at the locations corresponding to each layer's cross section, causing the powder particles to fuse together.

2.4 Materials Jetting

Materials jetting is used in 3D printing for bone tissue regeneration to create objects by selectively jetting droplets of materials onto a build platform. In materials jetting, liquid photopolymer resins or molten thermoplastic materials are used as the printing materials [17]. These materials are loaded into print cartridge or reservoirs within the 3D printer. For bioprinting applications, bioinks containing living cells or biomaterials may be used. The printer head moves over the build platform, selectively depositing material droplets onto the substrate according to the design of each layer. The droplets are precisely jetted onto the build platform using an array of nozzles or print heads.

2.5 Vat Photopolymerization

Vat photopolymerization primarily uses liquid photopolymer resins as the printing material. These resins are composed of monomers, oligomers, photoinitiators, and other additives [18]. The liquid photopolymer resin is poured into a transparent vat or reservoir attached to the 3D printer. The surface of resin is typically levelled to ensure uniformity. The 3D model is sliced into horizontal layers and the build platform is then lowered into the vat of resin, and a UV light source, such as laser or a digital light projector (DLP), selectively exposed each layer of the resin according to the design. When the UV light hits the resin, it triggers a photochemical reaction called photopolymerization. Photoinitiators in the resin absorb the UV light and initiate a chain reaction that causes the liquid resin to solidify and form a solid layer corresponding to the shape of the exposed cross-section of the 3D model.

3. CURRENT STUDIES ON 3D PRINTING FOR BONE TISSUE REGENERATION

In recent years, the field of 3D printing for bone tissue regeneration has emerged as a ground-breaking research, revolutionizing healthcare by seamlessly integrating cutting-edge technology with medical science. The union of additive manufacturing techniques with biological materials has unlocked various possibilities, ranging from personalized prosthetics to intricate organ scaffolds. Within this landscape, the pursuit of current studies in 3D printing technology for bone tissue regeneration stands as a testament quest for innovation in modern medicine. This exploration not only showcases the latest advancement in 3D printing methodologies but also underscores its profound impact on healthcare delivery, patient outcomes, and the very fabric of medical practice.

Bernardo and teammates [19] found in their study that SEM analysis clearly show that mesenchymal stem cells (MSC) efficiently adhere to the scaffold surface, and gradually change their cell morphology, from a spindle-like shape with round nuclei at day 7 (Figure 3) to an elongated shape with an increased number of cellular extensions after 14 and 21 days of culture. FDM technique was used to extrude PLA/HAp filament in which the twin screw extruder was used. The temperatures were set up at 180 °C at 5 heating zones. Meanwhile Zeng et. al. [20] used silicon nitride (Si_3N_4) as matrix for FDM due to their advantage in term of mechanical properties. Besides, Si_3N_4 has excellent biocompatibility and antibacterial performance. In addition, cells have good morphology and normal migration on the Si_3N_4 surface, making it as a very promising biomedical material. Zhao et. al. [21] explored in their study the effect of incorporation of dopamine methacrylamide oligomer (ODMA) into gelatin methacrylate GeIMA) on artificial organ substitute. They found that the surface assembly of these materials improved the cytocompatibility and mechanical properties of hydrogel. The hydrogel became more elastic and tougher and appropriate as artificial material for tissue engineering. UV photopolymerization was used to construct ODMA-GeIMA hydrogel.

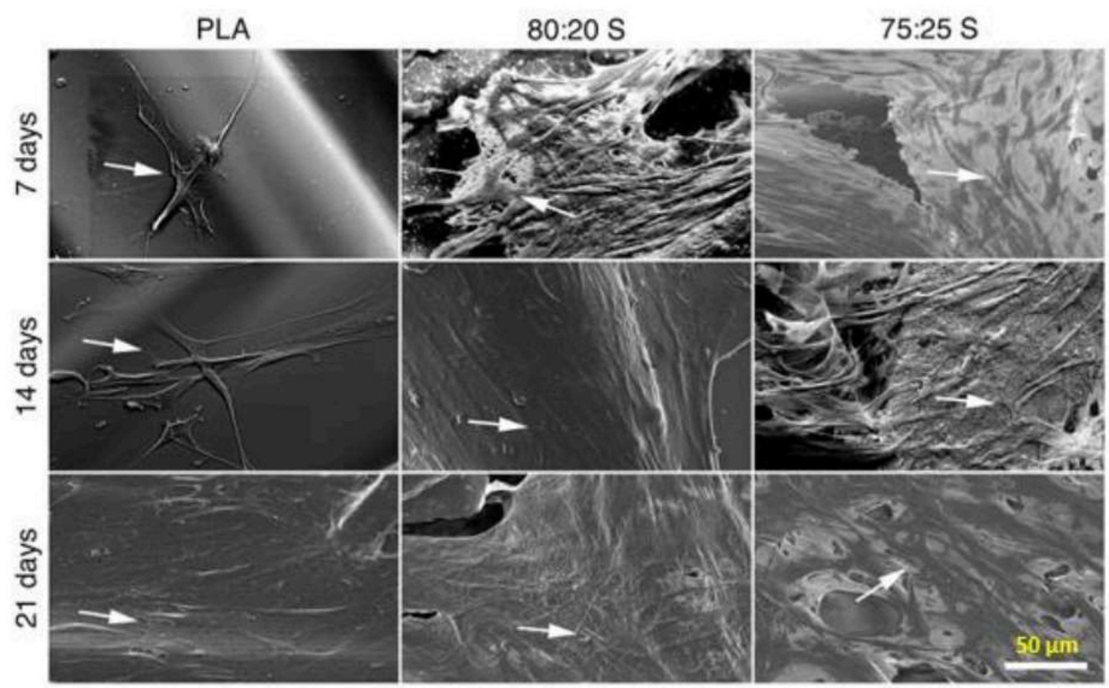

Figure 3: SEM images of MSC adhesion on PLA/HAp composite scaffolds after 7, 14, and 21 days of incubation with scale bar 50 μm [19]

On the other side, Vidakis et. Al. [22] explored the impact of Si_3N_4 as a strengthening agent for Biomed Clear resin through SLA. Their findings revealed that the enhanced dimensional precision and decreased porosity led to superior mechanical properties and electrical characteristics of the nanocomposite. Menezes et. al. [23] in their study developed polybutylene adipate-co-terephtalate (PBAT) coated with hydroxyapatite, bioglass, and gelatin using FDM. Their research indicated that applying a coating of any bioactive substance onto 3D printed PBAT scaffolds resulted in enhanced and promoted cell proliferation and pre-osteoblastic differentiation. Meanwhile, Kumar et. al. [24] used PLA coated with 316 L stainless steel printed on FDM 3D printer based on Taguchi's L-9 orthogonal array. They found that the optimum parameters give maximum tensile strength of 29.51 MPa and flexural strength of 98 MPa. A study done by Serino et. al. [25] contributed to a comprehensive understanding of FDM 3D-printed polyether-ether-2-ketone (PEKK). The tensile test revealed PEKK manufactured via FDM exhibits inferior mechanical properties in contrast to those produced using traditional manufacturing methods.

Shuai et. al. [26] prepared TiFeCrCoNi high entropy alloy using laser powder bed fusion. The alloy demonstrates good biocompatibility, an important aspect for orthopaedic implant and dental surgery. Mei et. al. [27] investigate the impact of material composition on the 3D printing, thermal, mechanical, and self-healing attributes utilizing linear polycaptrolactone (PCL) as a healing agent. Their experimentation unveiled that the addition of PCL improved mechanical properties and self-healing capabilities, while also decreasing the necessary printing exposure duration. Lauren and teammates study on direct ink writing (DIW) 3D printing double-quaternized chitosan (DQC) with cystamine-based non-isocyanate polyurethane (NIPU-Cys) in producing wound healing films [28]. The hydrogels were found to be suitable, producing porous, biocompatible hydrogels with valuable attributes for various wound-healing applications. On the other side, Manojit et. al. [29] used DIW to combine chicken bone extract and carbide in developing ceramic based orthopaedic implants. They conclude that sintering temperature has minimal effect and composition noticeable effect on mechanical strength as well as biotoxicity.

These studies highlight significant advancements in 3D printing technologies and biomaterials for tissue engineering and biomedical applications. Research on PLA/HAp, Si_3N_4, PBAT, and PEEK demonstrates their mechanical strength, biocompatibility, and potential for scaffold fabrication, while hydrogels like ODMA-GelMA and DQC-NIPU-Cys show promise for wound healing and artificial organ substitutes. The incorporation of self-healing agents, bioactive coatings, and metal reinforcement further enhances material durability, cytocompatibility, and osteogenic potential.

Table 2 shows current studies related to 3D printing technology for tissue regeneration. Based on selected literature, researchers commonly choose FDM for 3D printing over other method due to several factors. FDM is relatively inexpensive compared to other printing method such as stereolithography (SLA) or selective laser sintering (SLS). The printers themselves are often more affordable for research project with limited budget. FDM printers are also widely available and user-friendly. The printing process is straightforward, requiring minimal setup and maintenance. In addition, FDM supports a wide range of thermoplastic materials, including ABS, PLA, PETG, and TPU among others. The versatility allows researchers in choosing materials that suit the specific needs, whether it be for prototyping, functional arts, or bone tissue regeneration applications.

4. BIBLIOMETRIC ANALYSIS ON 3D PRINTING TECHNOLOGY FOR BONE TISSUE REGENERATION

The objective of this article is to identify the global trends in 3D printing technology research for bone tissue regeneration, focusing on metals, polymers, ceramics, composites, smart materials, and special materials. Data from Scopus database spanning the past decade, from 2015 onwards, was analyzed to discern patterns. The study has two main goals: firstly, to uncover the prevailing research directions in 3D printing technology for bone tissue regeneration, particularly regarding materials extrusion, directed energy deposition, powder bed fusion, materials jetting, and vat photopolymerization. Secondly, to conduct innovative research aimed at exploring the connection between cells response and applied materials as well as the production methods of the materials itself.

Table 2: Current studies related to biomedical 3D printing technology

Method	Material	Application	Reference
Fused Deposition Modeling (FDM)	Polylactic Acid (PLA) & Hydroxyapatite (HAp)	Biomedical Applications	[19]
Fused Deposition Modeling (FDM)	Silicon Nitride (Si_3N_4)	Bone Replacement	[20]
UV Photopolymerization	Dopamine Methacrylamide Oligomer (ODMA)& Gelatin Methacrylate (GeIMA)	Artificial Organ Substitute	[21]
Vat Photopolymerization	Biomed Clear (resin) & Silicon Nitride (Si_3N_4)	Biomedical Applications	[22]
Fused Deposition Modeling (FDM)	Poly(butylene adipate-co-terephtalate (PBAT)	Bone Tissue	[23]
Fused Deposition Modeling (FDM)	Polylactic Acid (PLA) & 316L Stainless Steel	Orthopedic Implant	[24]
Fused Deposition Modeling (FDM)	Polyether-ether-2-ketone (PEKK)	Biomedical Applications	[25]
Laser Powder Bed Fusion	TiFeCrCoNi Alloy	Orthopedic Implant & Dental Surgery	[26]
Masked Stereolithography Apparatus (MSLA)	Polycaptrolactone (PCL), 2-phenoxyethyl acrylate (POEA) & 1,6-hexanediol dimethacrylate (HDDMA)	Healing Agent	[27]
Direct Ink Writing (DIW)	Double-quaternized chitosan (DQC) & cystamine-based non-isocyanate polyurethane (NIPU-Cys)	Biomedical Applications	[28]
Direct Ink Writing (DIW)	Hydroxyapatite (HAp) & Silicon Carbide	Biomedical Applications	[29]

The bibliometric analysis, which forms the basis of this study, examines factors like publication count, types of publications, leading journals, authors, affiliations, and countries involved. However, it is important to note limitations associated with bibliometric data, such as its inability to provide a comprehensive measure of research quality. For instance, the articles with higher citation number reflect its impact rather than quality. Additionally, bibliometric analyses may not encompass entire research domains or index all publications, and comparison based solely on citation counts can be misleading due to the variations across disciplines. The study utilizes Scopus database as its primary data source, which is renowned for its vast collection of peer-reviewed literature.

Publication relevant to 3D printing technology in bone tissue regeneration, specifically those involving metals, polymers, ceramics, composites, smart materials, and special materials, were meticulously identified and retrieved. Various aspects of the retrieved data, such as publication years, subject categories, journal distributions, author collaborations, and citation metrics, were analyzed using bibliometric methods. The analysis covered period from 2015 to 2024, with the search query tailored to capture relevant publications. Social network analysis was employed for visualizing collaborative networks using software tools like Pajek and VosViewer. Both software is useful in navigating and mapping complex network. Raw data obtained from Scopus was processed and analyzed using Excel, leveraging its extensive features for bibliometric analysis.

5. WORLDWIDE TREND ON 3D PRINTING TECHNOLOGY IN BONE TISSUE REGENERATION

The categorization of publications constitutes a pivotal aspect of bibliometric analyses conducted on scientific literature. From an academic standpoint, publication type holds significant weight, influencing both scholarly progression and publication incentives. Table 3 illustrates that approximately 80% of the papers are articles for all materials including metals, polymers, ceramics, composites, smart materials and special materials. 218 articles related with 'polymers', 233 articles related with 'composites', and 76 articles related with 'metals' were discovered. Second most common form of publication is review with a total paper of 138, followed by book chapter (18 publications). The term 'other' refers to a conference review, editorial, erratum, short survey, and data paper.

Table 3: Types of published documents (2015-2024)

	Article	Review	Book Chapter	Conference Paper	Other
Metal	50	22	3	1	0
Polymer	171	32	6	8	1
Ceramic	135	27	3	5	1
Composite	187	32	5	9	0
Smart Material	26	15	1	0	0
Special Material	6	10	0	0	0

The high number of publications on composites and polymers suggests a strong focus on these materials for bone tissue engineering. This reflects the increasing use of biodegradable polymers (e.g. PLA, PCL) and bioactive composites (PLA/HAp, PCL/β-TCP) in scaffold fabrication due to their biocompatibility and tunable properties. With only 76 articles on metals, the data suggests a decline in the reliance on traditional metal implants in favour of bioresorbable alternatives. This indicates a shift toward more patient-friendly, biodegradable materials that integrate more naturally with bone tissue. The relatively low number of publications on smart materials suggests stimuli-responsive and bioactive materials such as shape-memory polymers and piezoelectric scaffolds are still emerging. Future research could explore bioactive materials that respond to mechanical, electrical, or biological stimuli for enhanced bone regeneration. The dominance of articles shows that most research efforts focus on experimental studies, which is crucial for clinical translation of materials. Meanwhile, the limited number of book chapters and conference papers suggests that more interdisciplinary collaborations and industry-academia discussions are needed to accelerate practical applications.

Table 4 presents an analysis of the most actively engaged and productive countries based on their publication output. China emerges as the leading contributor, securing the top position for publications related to metals, ceramics, composites, smart materials, and special materials. Specifically, China accounted for 29 publications (36.7%) on metals, 59 publications (30.9%) on polymers, 48 publications for ceramics (31.0%), and 72 publications (33.8%) on composites between 2015 and 2024. Following China, both the United States and India exhibit considerable participation, contributing 12 publications on metals. Similarly, the United Kingdom, Iran and South Korea demonstrate notable involvement, with 5 publications on metals. Regarding polymers, ceramic, and composite, South Korea trails China in publication output, with 29, 20, and 28 publications, respectively.

Table 4: Scientific publications by countries (2015-2024)

Country	Metal	Polymer	Ceramic	Composite	Smart Material	Special Material
China	29	59	48	72	15	6
USA	12	25	21	29	10	3
India	12	24	18	24	7	4
Iran	5	18	17	18	0	2
South Korea	5	29	20	28	2	0
United Kingdom	5	13	9	14	0	2
Turkey	3	8	7	8	0	2
Russian Federation	2	8	7	8	1	0
Australia	4	10	7	11	2	0
Sweden	2	2	1	2	0	0
Total	79	191	155	213	37	19

China has emerged as a leader in 3D printing technology for bone tissue regeneration, driven by substantial government funding, the establishment of specialized research centers, and collaborative projects with leading institutions. The Chinese government has strategically invested in regenerative medicine and 3D bioprinting to address healthcare challenges and position the nation at the forefront of medical innovation. A notable example is the National Key R&D Program, under which a research team from the University of Hong Kong's Department of Orthopaedics & Traumatology secured RMB 27.44 million. This funding supports the development of functional human tissues and organs, including bone, utilizing advanced 3D bioprinting technologies. The initiative underscores China's commitment to advancing bioprinting capabilities for clinical applications.

Several Chinese institutions have established dedicated centers to advance 3D bioprinting for bone tissue regeneration. A collaborative innovation center at Zunyi Medical University was approved by the Ministry of Education in October 2020. This center focuses on stem cell engineering and tissue regeneration. It boasts advanced platforms for molecular biology, cell analysis, and tissue engineering, contributing significantly to research in bone and joint injuries. Then, Medical 3D Printing Center of Excellence in Chongqing Fengdu was established with an initial investment of $7.5 million. This center specializes in producing customized implants and medical models to enhance surgical planning and outcomes. It exemplifies China's dedication to integrating 3D printing into clinical settings for bone repair.

On international collaboration, The Queensland University of Technology (QUT) in Australia, in partnership with Shanghai-based researchers, established a 3D bioprinting research center in Brisbane. This joint effort focuses on creating tissues to support the repair of aging bodies, highlighting China's role in global bioprinting research initiatives. Through strategic funding, the development of specialized research centers, and active participation in collaborative projects, China has positioned itself as a leading contributor to 3D printing technology for bone tissue regeneration.

Overall, the number of publications of all types of materials is dominated by China, South Korea, the United States, and India. Despite the South Korea comparatively lower publication counts than China for metals, it accrued substantial h-index of 14 for polymer, ceramic, and composite, indicating the high impact of its publications (Table 5). Notably, the United States and India show a quiet high h-index for polymers, 11 each, although the number of total of publications is much lower than China (Table 4). These findings suggest that the publications from these countries maintain a high level of quality. The nation with the highest h-index scores are China, the United States, and India for metals; China, South Korea, the United States, and India for polymers; and China, South Korea, India, and the United States for ceramics.

Table 5: H-index by countries (2015-2024)

Country	Metal	Polymer	Ceramic	Composite	Smart Material	Special Material
China	14	12	13	11	7	2
USA	6	11	9	12	5	3
India	6	11	9	11	3	3
Iran	5	8	8	8	0	2
South Korea	4	14	14	14	1	0
United Kingdom	3	8	7	8	0	1
Turkey	2	5	4	5	0	2
Russian Federation	3	4	5	6	2	1
Australia	3	7	5	8	1	0
Sweden	2	2	1	3	0	0

The high number on publication trends Figure 4 illustrates the presence of nine primary clusters, each characterized by the prevailing keywords within the domains of 3D printing technology in bone tissue regeneration.

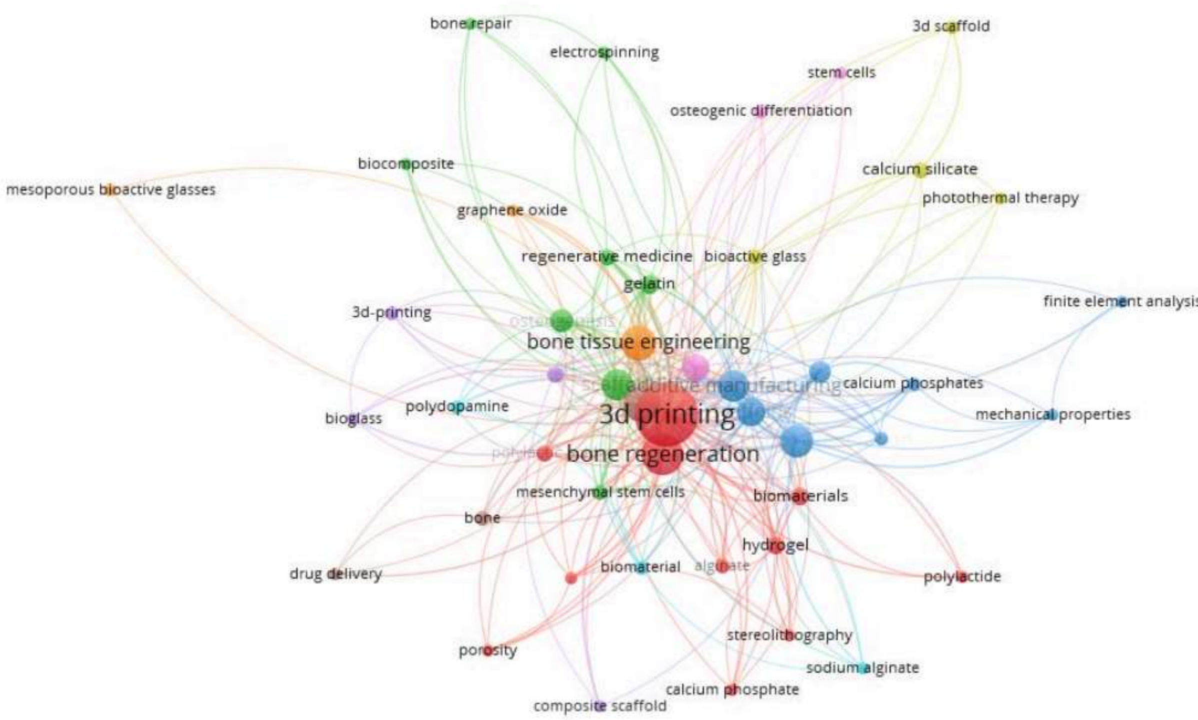

Figure 4: Author keywords map for 3D printing technology in bone tissue regeneration (2014-2023)

The strength of a relationship between two nodes is reflected in the distance between them. A shorter length indicates a closer relationship. A line connecting two keywords suggests that they have appeared together. The nodes with the same colour belong to the same cluster. Among the keywords that less occurred (3 times) were photothermal therapy, stem cells, finite element analysis, and mesoporous bioactive glasses with total link strength of 5, 5, 4, and 2, respectively. This might indicate the most recent topic in the area and most probably contain research gaps, which is a concern for further research. This analysis reflects the knowledge evolution of 3D printing and bone tissue regeneration research domains.

6. APPLICATIONS OF 3D PRINTING IN BONE TISSUE REGENERATION

3D printing has become a game-changing technology in the field of bone tissue regeneration, offering unprecedented precision and customization in the creation of bone scaffolds. The core of this innovation lies in the ability to produce intricate structures that closely replicate the natural architecture of bone. Traditional bone grafting techniques often face limitations in terms of size, shape, and assimilation with the host tissue [30,31], but 3D printing overcome these hurdles by allowing for the design and fabrication of patient-specific scaffolds. These scaffolds can be engineered with varying pore sizes, geometries, and mechanical properties to match the specific requirements of the bone defect being treated. For instance, the porosity of the scaffold can be meticulously controlled to ensure adequate space for new bone growth while maintaining structural integrity. One of the fundamental advantages of 3D printing in bone regeneration is its ability to use a variety of biomaterials that enhanced the scaffold's functionality. Biocompatible materials such as PLA, HAp, and TCP are commonly employed due to their compatibility with human tissue and their ability to support osteoconductivity, the process through which new bone cells migrate into scaffold and proliferate [32]. Advanced materials like bioactive glass can also be incorporated to stimulate bone formation through biochemical signals. These materials are often combined with growth factors, such as bone morphogenic proteins (BMPs), which can be embedded within the scaffold or coated onto its surface to promote faster and more effective bone regeneration [33].

Another significant advancement is the integration of stem cell technology with 3D printing. By seeding scaffolds with MSC, which have the potential to differentiate into bone-forming cells, researchers can enhance the regenerative capacity of the printed scaffolds [34]. The scaffolds provide a supportive matrix that facilitates cell adhesion and growth, while the stem cells contribute to new bone formation. This combination has shown potential in treating complex bone defects and critical-sized bone gaps that are difficult to address with conventional methods. In addition, 3D printing enables the creation of multi-material and multi-functional constructs that can address specific clinical needs. For examples, scaffolds can be designed with gradients of material properties to mimic the transition from bone to soft tissue or to include embedded channels for the delivery of nutrients and drugs [35]. This level of customization and sophistication is difficult to achieve with traditional manufacturing techniques. The future of 3D printing in bone tissue regeneration holds even greater promise with ongoing research and technological advancements. Innovations such as bioprinting, which involves printing living cells and biological materials, are paving the way for the development of more complex and functional bone tissues. As these technologies continue to evolve, they are expected to significantly improve the outcomes of bone repair and regeneration, offering new hope for patients with challenging bone injuries and conditions.

However, several challenges and limitations hinder its clinical translation. Printed scaffolds often lack sufficient strength compared to native bone, especially in load-bearing applications such as femoral and spinal implants. Materials like polymers have low mechanical strength and stiffness making them unsuitable for high-stress environments. Metallic scaffolds such as titanium and magnesium alloys provide high mechanical strength, but they lack bioresorbability, leading to long term complications. Besides, scaffolds must degrade at the controlled rate, allowing new bone to grow while maintaining structural support. Mismatched degradation can lead to implant failure.

7. CONCLUSIONS

3D printing technology produce complex-shaped parts which are impossible to produce using traditional methods. The production is cost effective, timesaving, and easier. In the realm of bone tissue regeneration, its myriad benefits render it a staple, continually garnering preference for various applications within the field. Numerous applications abound in the biomedical domain, spanning surgical procedures employing biomodels, advanced modelling and imaging techniques for enhanced disease comprehension, fabrication of medical devices, customized implants and prostheses tailored to individual patients, veterinary medical uses, tissue engineering endeavours, pharmaceutical industry applications, and the ongoing experimental phase of organ bioprinting.

Moreover, the utilization of generated 3D models significantly heightens the precision of surgical interventions when compare with radiographic and clinical assessments. This advancement not only proves invaluable for surgeons but also extends its advantages to veterinarians. Additionally, this approach garners preference in crafting personalized prostheses and implants. The enhanced quality of life experienced by numerous patients is directly attributable to implants and prostheses that can be meticulously tailored in size and colour, mirroring patient's unique anatomy.

3D printing technology also enables the production of biomimetic 3D structures resembling natural tissues. Its utilization has expanded to encompass tissue engineering, aiming to fabricate biological substitutes for various body tissues and organs not only limited to bone, but also skin, cartilage, vasculature, and nervous systems. Over the past two decades, significant strides have been made in biomedical field through 3D printing. With ongoing advancements in 3D printing technologies, materials science, and biological science, it is foreseeable that despite the challenges ahead, a number of innovative 3D-printed biomedical products will soon be available for clinical applications.

Acknowledgements

Authors would like to thank Universiti Tun Hussein Onn Malaysia (UTHM) through the funding via Tier 1 grant Q495.

Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare

Compliance with Ethical Standards

The work is compliant with ethical standards

References

[1] Sun, H., Zou, B., Wang, X., Chen, W., Zhang, G., Quan, T. & Huang, C. (2024). Advancements in multi-material additive manufacturing of advanced ceramics: a review of strategies, techniques and equipment. *Materials Chemistry and Physics,* 319, 129337.

[2] Tripathi, S., Mandal, S. S., Bauri, S. & Maiti, P. (2023). 3D bioprinting and its innovative approach for biomedical applications. *MedComm*, 4(1), e194.

[3] Reddy, V. S., Ramasubramaniam, B., Telrandhe, V. M. & Ramakrishna, S. (2023). Contemporary standpoint and future of 3D bioprinting in tissue/organs printing. *Current Opinion in Biomedical Engineering*, 27, 100461.

[4] Olawade, D.B., Marinze, S., Qureshi, N., Weerasinghe, K., & Teke, J. (2025). Transforming organ donation and transplantation: strategies for increasing donor participation and system efficiency. *European Journal of Internal Medicine*, 133, 14-24.

[5] Cardoso, P. H. N. & Araujo, E. S. (2024). An approach to 3D printing techniques, polymer materials, and their applications in the production of drug delivery systems. *Compounds,* 4(1), 71-105.

[6] Parihar, A., Parihar, D. S., Gaur, K., Arya, N., Choubey, V. K. & Khan, R. (2024). 3D bioprinting for drug development and screening: recent trends towards personalized medicine. *Hybrid Advances*, 7, 100320.

[7] Sousa, A. C., Alvites, R., Lopes, B., Sousa, P., Moreira, A., Coelho, A., Santos, J. D., Atayde, L., Alves, N. & Mauricio, A. C. (2025). Three-dimensional printing/bioprinting and cellular therapies for regenerative medicine: current advances. *Journal of Fucntional Biomaterials*, 16(1), 28.

[8] Yang, H., Fang, H., Wang, C., Wang, Y., Qi, C., Zhang, Y., Zhou, Q., Huang, M., Wang, M. & Wu, M. (2023). 3D printing of customized functional devices for smart biomedical systems. *Smart Materials*, 5(5), e1244.

[9] Ali, F., Kalva, S.N. & Koc, M. (2024). Advancements in 3D printing techniques for biomedical applications: a comprehensive review of materials consideration, post processing, applications, and challenges. *Discover Materials,* 4, 53.

[10] Park, S., Shou, W., Makatura, L., Matusik, W. & Fu, K. (2022). 3D printing of polymer composites: materials, processes, and applications. *Matter,* 5(1), 43-76.

[11] Heide, D., Cidonio, G., Stoddart, M. J. & D'Este, M. (2022). 3D printing of inorganic-biopolymer composites for bone regeneration. *Biofabrication*, 14, 042003.

[12] He, L., Yin, J. & Gao, X. (2023). Additive manufacturing of bioactive glass and its polymer composites as bone tissue engineering scaffolds: a review. *Bioengineering (Basel)*, 10(6), 672.

[13] Syriybayev, D., Zharylkassyn, B., Seisekulova, A., Akhmetov, M., Perveen, A. & Talamona, D. (2021). Optimisation of strength properties of FDM printed parts—a critical review. *Polymers,* 13(10), 1587.

[14] Zhang, W., Xu, C., Li, C. & Wu, S. (2024). Advances in ultrasonic-assisted directed energy deposition (DED) for metal additive manufacturing. *Crystals,* 14(2), 114.

[15] Dezaki, M. L., Serjouei, A., Zolfagharian, A., Fatouhi, M., Moradi, M., Ariffin, M. K. A. & Bodaghi, M. (2022). A review on additive/subtractive hybrid manufacturing of directed energy deposition (DED) process. *Advanced Powder Materials,* 1(4), 100054.

[16] Joshua, R. J. N., Raj, S. A., Sultan, M. T. H., Lukaszewicz, A., Jozwik, J., Oksiuta, Z., Dziedzic, K., Tofil, A. & Shahar, F. S. (2024). Powder bed fusion 3D printing in precision manufacturing for biomedical applications: a comprehensive review. *Materials (Basel),* 17(3), 769.

[17] Pandele, A. M., Constantinescu, A., Radu, I. C., Miculescu, F., Voicu, S. I. & Ciocan, L. T. (2020). Synthesis and characterization of PLA-micro-structured hydroxyapatite composite films. *Materials,* 13(2), 274.

[18] Shah, M., Ullah, A., Azher, K., Rehman, A. U., Juan, W., Akturk, N., Tufekci, C. S. & Salamci, M. U. (2023). Vat photopolymerization-based 3D printing of polymer nanocomposites: current trends and applications. *RSC Advances,* 13(2), 1456-1496.

[19] Madheswaran, S., Sivakumar, K., Sofiene, H. & Irfan, A. (2024). Structural, mechanical, and in-vitro characterization of hydroxyapatite loaded PLA composites. *Journal of Molecular Structure,* 1306, 137862.

[20] Zeng, X., Sipaut, C. S., Ismail, N. M., Liu, Y., Farm, Y. Y. & He, J. (2024). Mechanical properties and biological activity of 3D printed silicon nitride materials. *Ceramics International,* 50(9), 16704-16713.

[21] Zhao, Q., Du, H., Li, Y., Wang, J., Wang, Y., Zhang, Q. & Wen, S. (2024). Layer-by-layer self-assembly method improves the performance and cytocompatibility of 3D printing ODMA-GelMA hydrogel. *Materials Letters,* 363, 136266.

[22] Vidakis, N., Petousis, M., Michailidis, N., David, C., Saltas, V., Sagris, D., Spiridaki, M., Arygyros, A., Mountakis, N. & Papadakis, V. (2024). Interpretation of the optimization course of silicon nitride nano-powder content in biomedical resins for vat photopolymerization additive manufacturing. *Ceramics International,* 50(9), 14919-14935.

[23] Menezes, F. C., Scheibel, J. M., Balbinot, G. S., Miranda, G. M., Leitune, V. C. B., Collares, F. M. & Soares, R.M.D. (2024). Bioactive materials-coated polybutylene-adipate-co-terephthalate 3D-printed scaffolds for application in the bone tissues engineering. *Polymers for Advanced Technologies,* 35(4), e6373.

[24] Kumar, R., Kumar, M. & Chohan, J. S. (2024). Investigation of tensile and flexural property of 316L stainless steel-coated polylactic acid parts. *Journal of Materials Engineering and Performance,* 33(6), 3087-3100.

[25] Serino, G., Distefano, F., Zanetti, E. M., Pascoletti, G. & Epasto, G. (2024). Multiscale mechanical characterization of polyether-2-ketone (PEKK) for biomedical application. *Bioengineering,* 11(3), 244.

[26] Cijun, S., Jiading, X., Xihao, J., Shuping, P. & Chunming, W. (2024). Additively manufactured high entropy alloy with high wear resistance for biomedical implant. *Vacuum,* 221, 112939.

[27] Mei, V., Schimmelpfennig, K., Caravaca, E., Colvin, S. & Lewis, C. L. (2024). Investigating the structure-property−processing relationship of polycaprolactone-based 3D printed self-healing polymer blends. *Applied Polymer Materials,* 6(4), 2177-2187.

[28] Lauren, I., Farzan, A., Lindfors, N. C. & Seppala, J. (2024). Direct ink writing of biocompatible chitosan/non-isocyanate polyurethane/cellulose nanofiber hydrogels for wound-healing applications. *International Journal of Biological Macromolecules,* 259(2), 129321.

[29] Das, M., Dixit, A., Jana, A., Karthik, R., Seeram, P. R., Bora, H., Dhara, S., Panda, S. K. & Tiwary, C. S. (2024). Enhanced toughness and strength of 3D printed carbide-oxide composite for biomedical applications. *Journal of the Mechanical Behaviour of Biomedical Matarials,* 150, 106290.

[30] Hussin, M. S. F., Abdullah, H. Z., Idris, M. I. & Wahab, M. A. A. (2022). Extraction of natural hydroxyapatite for biomedical applications—a review. *Heliyon,* 8(8), e10356.

[31] Hussin, M. S. F., Serah, A. M., Azlan, K. A., Abdullah, H. Z., Idris, M. I., Ghazali, I., Shariff, A. H. M., Huda, N. & Zakaria, A. A. (2021). A bibliometric analysis of the global trend of using alginate, gelatine, and hydroxyapatite for bone tissue regeneration applications. *Polymers,* 13(4), 647.

[32] Krishani, M., Shin, W. Y., Suhaimi, H. & Sambudi, N. S. (2023). Development of scaffolds from bio-based natural materials for tissue regeneration applications: a review. *Gels,* 9(2), 100.

[33] Zhou, W. T., Shi, P. K., Dong, J. B., Li, S. J., Lu, P. J. & Liu, C. (2022). Scaffolds of bioactive glass combined with recombinant human bone morphogenetic protein -9 (rhBMP-9) for tooth extraction site preservation. *Heliyon,* 8(1), e08796.

[34] Gharibshahian, M., Salehi, M., Beheshtizadeh, N., Farahani, M. K., Atashi, A., Nourbakhsh, M. S. & Alizadeh, M. (2023). Recent advances on 3D-printed PCL-based composite scaffolds for bone tissue engineering. *Frontiers in Bioengineering and Biotechnology,* 11, 1168504.

[35] Alhabshi, M. O., Aldhohayan, H., Baeissa, O. S., Al Shehri, M. S., Alotaibi, N. M., Almubarak, S. K., Al Ahmari, A. A. & Khan, H. A. (2023). Role of three-dimensional printing in treatment planning for orthognathic surgery: a systematic review. *Cureus,* 15(10), e47979.