Applied Science and Technology Research Journal
e-ISSN : 2963-6698
Volume 4 Nomor 2, November 2025
https://journal.upy.ac.id/index.php/ASTRO/index

Technology Trends, Innovations, and Future Research Directions in 3D Printing (Additive Manufacturing): A Systematic Literature Review

Banu Santoso*[1], Dhananjaya Yama Hudha Kumarajati[1], Herianto[1], Muhammad Kusumawan Herliansyah[1], Alva Edy Tontowi[1]
[1]Departemen Teknik Mesin dan Industri, Fakultas Teknik, Universitas Gadjah Mada, Yogyakarta, Indonesia
Email: *[1]banu@amikom.ac.id

Abstract

3D printing or Additive Manufacturing (AM) technology has experienced rapid growth in the past five years, driven by the integration of new technologies such as artificial intelligence (AI), bio- and nano-composite materials, and blockchain-based security systems. This study aims to analyze technology trends, key innovations, and predict future research directions in AM using a Systematic Literature Review (SLR) approach to 80 Scopus/WoS indexed articles. The results show that AI plays a central role in improving production efficiency and accuracy, while material innovations expand AM applications to the medical and aerospace sectors. In addition, the application of 4D printing and blockchain is beginning to form a new paradigm in intelligent and decentralized manufacturing. The 2025–2030 research roadmap compiled from these findings shows a strategic focus on adaptive AI, multifunctional bioinks, modular manufacturing systems, and full integration between AM, blockchain, and smart materials. This study not only identifies research trends and gaps but also offers strategic contributions to the development of future AM technologies in a more adaptive, sustainable, and secure manner.

Keywords: *3D Printing; Additive Manufacturing; Technology Trends; Material Innovation; Artificial Intelligence*

1. INTRODUCTION

Additive Manufacturing (AM) popularly known as three-dimensional (3D) printing has emerged as one of the most transformative production technologies of the twenty-first century [1], [2]. By fabricating components through the layer-by-layer addition of material directly from digital data, AM overturns the logic of subtractive and formative techniques that have dominated manufacturing since the first industrial revolution [3]. What began in the late 1980s as a laboratory-scale method for rapidly prototyping plastic parts has matured into a versatile platform capable of producing geometrically complex [4], functionally graded [5], and fully customised artefacts in polymers [6], metals [7], ceramics [8], composites [9] and even living tissues [10], [11], [12]. As a consequence, AM now underpins strategic initiatives in aerospace [13], automotive [14], biomedical engineering [15], energy [16], architecture[17], cultural heritage [18] and defence [19], and it is increasingly cited by policy makers as a pillar of digitalisation and sustainable industrial growth [20], [21]. Within the broader discourse of the Fourth Industrial Revolution, AM represents a tangible manifestation of cyber-physical convergence: design files circulate in cyberspace while physical objects are materialised on demand at the edge of the network, collapsing traditional boundaries between design studios, factory floors and end users [22].

The pace and direction of AM research have diversified markedly over the past decade. Early efforts focused on improving dimensional accuracy, expanding material portfolios, and reducing the cost of hardware [23]; however, the research frontier has since shifted toward systemic integration, process intelligence and ecological impact [24], [25]. Multilaser powder-bed fusion systems now attain build rates orders of magnitude higher than their predecessors, digital light processing achieves sub-micron resolutions in photosensitive resins, and wire-arc additive manufacturing can deposit kilograms of metallic feedstock per hour for large-scale structural parts [26], [27]. Simultaneously, bioprinting has progressed from simple hydrogel scaffolds to vascularised soft tissues, while concrete and clay printing techniques promise to reshape the construction sector [28]. This remarkable diversification has been enabled by concomitant advances in simulation, sensing, and data analytics that allow researchers to interrogate the intricate couplings between heat transfer, phase transformation, rheology and structural integrity that govern layerwise fabrication processes [29].

Between 2019 and 2024 the field entered an acceleration phase driven by the convergence of four technological currents: artificial intelligence (AI) [30], [31], advanced functional materials [32], [33], four-dimensional (4D) printing [34], [35], [36], and blockchain-secured digital threads [37], [38]. Machine-learning algorithms trained on high-resolution process data now predict porosity, warpage and residual stress before a single layer is deposited, while closed-loop controllers adjust scan speed, laser power or extrusion temperature in real time to avert defects and reduce scrap [39], [40]. On the materials front, nano-reinforced polymers, high-entropy alloys and ceramic matrix composites considerably extend the mechanical envelope of printable parts, whereas bioinks enriched with growth factors and living cells open unprecedented avenues in regenerative medicine [41]. The notion of 4D printing—objects that morph in response to thermal, magnetic, moisture or optical stimuli—adds a temporal dimension that blurs the line between manufacturing and actuation, enabling deployable aerospace structures, adaptive wearables and self-healing implants [42]. Finally, distributed-ledger architectures have begun to safeguard the intellectual property embedded in digital design files, authenticate spare parts, and orchestrate decentralised production networks, thereby addressing one of the most persistent barriers to enterprise adoption of AM [43].

These breakthroughs coincide with profound economic and societal imperatives. Global supply-chain disruptions exemplified by the COVID-19 pandemic, geopolitical tensions and climate-induced hazards have exposed the fragility of just-in-time, geographically stretched production models [44]. Governments and industries now view AM as a means to reshore critical manufacturing, shorten lead times and customise products without incurring the tooling costs of conventional methods. Moreover, AM's capacity to consolidate multi-part assemblies into monolithic structures, to fabricate lightweight lattices with minimal material usage and to enable repair rather than replacement aligns closely with the principles of the circular economy and carbon-neutral manufacturing [45]. Yet the technology's environmental credentials remain contested: high-energy laser processes, feedstock purification and post-processing steps can offset the material savings if not carefully optimised [46]. Understanding the full life-cycle performance of AM therefore constitutes both a research challenge and a policy priority [47].

Despite its promise, the field faces persistent obstacles that hinder large-scale diffusion. The absence of standardised, domain-specific datasets limits the transferability of AI models across machine vendors and material systems; qualification protocols for novel bio- and nano-composites lag behind laboratory discoveries; and robust design tools for 4D printing remain in their infancy [48], [49]. Moreover, interoperability issues plague the integration of blockchain with legacy manufacturing execution systems, while regulatory frameworks struggle to keep pace with distributed, on-demand production scenarios. Bridging these gaps requires a concerted interdisciplinary effort that blends materials science, mechanical engineering, computer science, data governance and industrial economics. A clear picture of where breakthroughs have occurred, where bottlenecks persist, and which research avenues hold the greatest transformative potential is therefore indispensable for academics, practitioners and policy makers who must allocate resources, craft standards and chart technological roadmaps.

This paper addresses that need by offering a systematic, evidence-based analysis of technology trends, innovation trajectories and prospective research directions in additive manufacturing. Drawing on eighty peer-reviewed journal articles published between 2019 and 2024 and indexed in Scopus and Web of Science, we map the thematic landscape of contemporary AM research, identify the technological clusters that have gained momentum, and distil the cross-cutting gaps that impede industrial uptake. We then extrapolate a 2025–2030 roadmap that highlights milestones in adaptive AI control, multifunctional bioinks, modular high-throughput hardware, and blockchain-enabled supply-chain security, situating each milestone within broader debates on sustainability, workforce skills and regulatory oversight. By synthesising these insights into a cohesive narrative, the study aims not only to chronicle past accomplishments but also to orient future investigations toward the most impactful and societally relevant frontiers. Ultimately, we contend that the evolution of additive manufacturing from a prototyping tool to a cornerstone of intelligent, resilient and sustainable production hinges on the community's ability to integrate digital intelligence, advanced materials and secure data infrastructures into a harmonious socio-technical ecosystem.

2. RESEARCH METHODOLOGY

This study adopts a Systematic Literature Review (SLR) methodology to explore the current state and future direction of research in the field of 3D printing, also known as additive manufacturing (AM). The SLR approach is chosen for its ability to provide a comprehensive, transparent, and replicable synthesis of existing knowledge based on clearly defined search protocols and analytical criteria. Following the guidelines of PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), the review process ensures a rigorous and structured examination of the literature, from data identification to article selection, evaluation, and synthesis.

The review focused on identifying and analyzing trends, technological innovations, and projected research directions in AM between 2019 and 2024. This time frame was selected to capture the most recent advancements in the field, particularly the convergence of AM with artificial intelligence, advanced materials, 4D printing, and blockchain. To obtain a representative and high-quality sample of scholarly work, four major academic databases were selected as primary sources: Scopus, Web of Science (WoS), IEEE Xplore, and ScienceDirect. These databases are widely recognized for indexing peer-reviewed journals with high academic credibility, especially in engineering, technology, and applied sciences. The search strategy employed a combination of keywords to ensure comprehensive coverage. The Boolean string used was: ("3D printing" OR "additive manufacturing") AND ("technology trends" OR innovations OR "future research directions") AND (2019–2024). This query was applied to the titles, abstracts, and keywords of articles indexed in the selected databases. To increase coverage, supplementary searches were conducted using secondary sources such as white papers, industrial reports, and patent documents from organizations like the European Patent Office (EPO), yielding an additional set of articles relevant to technological developments in AM.

The initial search yielded a total of 670 articles (624 from academic databases and 46 from secondary sources). Duplicate entries were removed using reference management software (Mendeley and Zotero), resulting in 530 unique articles. The screening phase involved a review of the titles and abstracts to assess relevance, narrowing the pool down to 340 articles. Next, full-text evaluations were conducted on 120 articles to determine their eligibility based on predefined criteria. The inclusion criteria required that articles be (1) peer-reviewed, (2) published in English between January 2019 and March 2024, (3) focused on technological trends, innovations, or future research directions in AM, and (4) based on experimental studies, reviews, or analytical models related to manufacturing technologies. Articles were excluded if they were (1) non-peer-reviewed (e.g., editorials, commentaries), (2) focused solely on economic or business implications without technical analysis, (3) abstracts of conference proceedings without accompanying full papers, or (4) written in languages other than English.

Upon applying these criteria, 80 articles were deemed suitable for in-depth analysis. These articles span diverse domains including aerospace, biomedical engineering, materials science, computer-aided manufacturing, and industrial informatics. To extract structured insights from the selected articles, a detailed data coding process was conducted. Each article was analyzed to identify its year of publication, primary focus (e.g., AI integration, material innovation, blockchain implementation), type of technological advancement, cited research gaps, and proposed directions for future studies. The analysis phase combined qualitative and quantitative techniques. A thematic analysis was conducted to identify recurring patterns and central themes across the literature. These themes were categorized into dominant technology clusters such as AI-driven process control, advanced materials (bio and nano composites), 4D printing for smart applications, high-speed AM systems, and blockchain-based security. In parallel, a quantitative mapping of topic frequencies was used to track the growth of specific research themes over time, offering a macroscopic view of where academic focus has intensified.

To enrich the analysis, a comparative sectoral study was performed, contrasting research outcomes and technology adoption rates in different domains (e.g., medical vs. aerospace). This helped highlight domain-specific challenges, such as biocompatibility requirements in medical applications or thermal stability in aerospace-grade materials. Additionally, the study developed a forecasting roadmap for 2025–2030, synthesizing evidence from multiple articles to propose a timeline of anticipated breakthroughs, such as the commercialization of adaptive AI controllers, the standardization of blockchain protocols for AM, and the emergence of multifunctional smart materials. Throughout the process, efforts were made to ensure validity and reliability. Cross-validation was applied by involving two independent researchers in article screening and classification to minimize bias. Triangulation was also used by integrating findings from journal articles, white papers, and patent analyses to form a multidimensional view of the field. An audit trail of all methodological decisions was maintained to support future replications or extensions of the study. Nonetheless, some limitations of the methodology must be acknowledged. The review was restricted to English-language publications, potentially overlooking significant findings in other languages. The five-year time frame, while capturing recent developments, may omit slower-evolving trends that require longer observation periods. Additionally, the interpretation of future research directions relies in part on expert opinions expressed in the literature, which may carry subjective biases. In summary, the research methods used in this study are designed to offer a robust and replicable approach to mapping the evolution and future trajectory of 3D printing technologies. By systematically analyzing the most relevant and recent literature, this study aims to contribute not only to academic discourse but also to strategic decision-making in industry and policy related to the advancement of additive manufacturing in the era of Industry 4.0 and beyond.

3. RESULTS AND DISCUSSION

The systematic screening of eighty peer-reviewed articles published between January 2019 and March 2024 reveals five tightly interwoven research streams that are shaping the contemporary additive-manufacturing (AM) landscape: (i) AI-driven process intelligence, (ii) advanced functional materials, (iii) high-throughput hardware architectures, (iv) 4D printing of smart, stimuli-responsive structures, and (v) blockchain-secured digital supply chains. Although each stream is advancing at its own cadence, the corpus shows a strong convergence toward fully autonomous, data-centric production ecosystems in which material formulation, process control, quality assurance, and cyber-security are co-designed rather than treated as isolated problems.

3.1 AI-Driven Process Intelligence

Forty-nine of the analysed papers (61%) apply machine-learning or deep-learning techniques to at least one stage of the AM workflow [30], [50], [51], [52], [53]. Two dominant sub-themes emerge. First, defect prediction and mitigation: convolutional neural networks trained on in-situ melt-pool images or extrusion-pressure signals now classify porosity, layer delamination, or warpage with accuracies routinely exceeding 90%. Several authors report closed-loop controllers that alter laser power, scan speed, or nozzle temperature in real time, cutting scrap rates by 20–30 % relative to open-loop baselines [54], [55], [56], [57], [58], [59]. Second, adaptive slicing and tool-path planning: reinforcement-learning agents re-distribute layer thickness dynamically, concentrating resolution only where it is functionally critical [60], [61], [62], [63]. Across the dataset, mean build times fall by 15–25 % without loss of geometric fidelity. These results confirm AI's dual role as both a predictive and a prescriptive engine, yet they also expose recurring barriers: (a) the lack of large, standardised, cross-machine datasets limits model transferability, and (b) industrial stakeholders remain wary of "black-box" algorithms that cannot provide actionable explanations when production deviates from specification . Explainable-AI frameworks—mentioned in only six papers—thus constitute a sparsely researched but pivotal frontier.

3.2 Advanced Functional Materials

Thirty-three articles (41 %) focus on feed-stock innovations. Nanocomposite polymers doped with graphene, silicon-carbide whiskers, or carbon nanotubes achieve tensile-strength gains of up to 40 % and thermal-conductivity increases of an order of magnitude over neat polymers, enabling lightweight heat exchangers and drone airframes. High-entropy alloys (HEAs) appear in seven studies, where multi-principal-element chemistries suppress hot cracking in laser-powder-bed fusion (LPBF) and deliver elongations above 15 % at room temperature—remarkable for additively manufactured metals. The biomedical literature, by contrast, is dominated by bioinks enriched with decellularised extracellular matrix or growth factors; successful vascularisation of centimetre-scale constructs is repeatedly demonstrated, but long-term in vivo stability beyond twelve weeks is seldom addressed. A sideways innovation that garners increasing attention is sustainable feed-stock sourcing—for example, depolymerised PET filaments or recycled titanium powders derived from aerospace scrap. Life-cycle assessments (LCAs) included in five papers suggest that cradle-to-gate CO_2 emissions can be cut by 25 % compared with virgin materials, provided that energy-intensive atomisation steps are offset by renewable electricity. Collectively, the results underscore that material science is no longer a peripheral enabler but a co-driver of AM's industrial viability.

3.3 High-Throughput Hardware Architectures

Speed and scalability issues constitute the third pillar of innovation. Multi-laser LPBF systemssome employing as many as twelve 400-W lasersnow attain deposition rates exceeding 500 $cm^3\ h^{-1}$, an order-of-magnitude leap over single-laser predecessors. Conveyor-belt fused-filament-fabrication (FFF) platforms, meanwhile, exploit continuous Z-motion to print objects of theoretically unlimited length, reducing downtime between jobs to minutes. In vat-photopolymerisation, continuous-liquid-interface production (CLIP) and volumetric computed axial lithography drive vertical build speeds above 300 mm h^{-1}. Industrial case studies document cost break-even points relative to injection moulding at batch sizes up to 10 000 units for small polymer parts—an inflection that could dissolve the traditional prototype-versus-production dichotomy. However, the literature also highlights three persistent bottlenecks: thermal-stress accumulation in large LPBF builds [64], [65], resin depletion dynamics limiting volumetric photopolymerisation [66], and the capital-expense premium of multi-laser systems [67], [68], [69]. Addressing these constraints demands co-optimised thermal-management strategies and modular hardware designs that can be scaled incrementally rather than purchased as monolithic investments.

3.4 4D Printing and Stimuli-Responsive Structures

Twenty-one studies (26 %) engage with 4D printing, wherein printed artefacts morph in response to external stimuli such as heat, moisture, pH, or electromagnetic fields. Shape-memory polymers (SMPs) remain the dominant material class, but a notable shift toward hydrogel-metal hybrids and magnetically actuated elastomers is evident. Demonstrated applications include self-deploying aerospace booms, drug-eluting stents that expand at body temperature, and adaptive fashion garments. From a mechanical standpoint, bending angles of 120–180 ° are routinely achieved, yet fatigue lifetimes under cyclic actuation rarely exceed 10^3 cycles insufficient for many service environments. Computational design tools also lag: only four papers report inverse-form-finding algorithms capable of predicting final shapes after stimulus exposure. The field is thus rich in proof-of-concepts but immature in durability data, predictive modelling, and integration with mainstream CAD environments. Bridging these gaps will be essential before 4D printing migrates from laboratory demonstrations to certified industrial products.

3.5 Blockchain-Secured Digital Supply Chains

Although discussed in just eleven papers (14 %), blockchain integration stands out for its strategic implications. Authors converge on three principal use-cases: immutable design-file vaults, licence-controlled remote printing, and chain-of-custody verification for critical spare parts. Pilot deployments on permissioned ledgers (e.g., Hyperledger Fabric) prove technically feasible, but scalability and energy consumption remain under-explored. Moreover, interoperability with existing manufacturing-execution systems is hampered by proprietary machine firmware and the absence of standard application-programming interfaces (APIs). The review reveals a nascent but growing consensus that consortium-led standardisation analogous to the PCI-DSS framework in finance—will be required to unlock broad adoption. Until then, blockchain solutions are likely to remain confined to high-value, low-volume defence and aerospace supply chains where the cost of counterfeiting outweighs the overheads of distributed-ledger infrastructure.

3.6 Cross-Cutting Performance Metrics and Sustainability

Across all five streams, three performance metrics recur as decisive adoption levers: build quality, throughput versus cost, and environmental footprint. On quality, the fusion of AI monitoring with advanced sensors (thermo-emission cameras, high-speed interferometry) consistently outperforms human inspection, yet the scarcity of traceable calibration artefacts complicates inter-laboratory benchmarking. On cost, multi-laser and conveyor-belt systems dramatically lower per-part expense above certain volume thresholds, but amortisation periods remain sensitive to machine utilisation rates. Finally, sustainability analyses diverge: ten studies report net environmental gains when AM replaces subtractive machining of high-buy-to-fly-ratio aerospace parts, whereas six studies caution that powder-production energy demand can negate such benefits unless powered by renewables. Consensus therefore emerges that AM is potentially sustainable, contingent on feed-stock recycling, green electricity, and design strategies that exploit lattice structures to minimise material usage.

3.7 Research Gaps and Future Directions

Synthesising the above findings, four cross-cutting gaps crystallise. (1) Standardised, open-access datasets: without them, AI models remain bespoke and non-transferable. (2) Multi-stimuli, fatigue-resistant smart materials: essential for durable 4D-printed components. (3) Modular, energy-efficient high-throughput hardware: required to democratise AM beyond capital-intensive niches. (4) Interoperable blockchain frameworks: pivotal for secure, distributed manufacturing. Addressing these gaps will demand interdisciplinary consortia that unite materials scientists, computer-vision engineers, hardware designers, and legal scholars.

3.8 Implications for Industry, Academia, and Policy

For industry, the results endorse a phased adoption strategy: near-term value lies in AI-enabled quality assurance and high-speed polymer printing for customised consumer goods, whereas investment in 4D printing or blockchain should be piloted in low-risk contexts until standards mature. For academia, the need for explainable machine-learning models, fatigue-data repositories for smart materials, and physics-informed simulations of volumetric curing offers fertile research territory. For policy makers, the mixed sustainability evidence implies that carbon-labelling schemes, renewable-energy incentives, and recycling mandates will be critical to steer AM toward genuine environmental benefit. Harmonised standards for data formats, material testing, and digital-thread security would further catalyse cross-sector adoption.

3.9 Synthesis and Outlook

The corpus analysed paints a picture of additive manufacturing at an inflection point: core technologies are maturing from experimental novelties into industrial workhorses, yet systemic integration challenges remain. AI lubricates process intelligence, advanced materials widen application horizons, high-throughput hardware drives economic feasibility, 4D printing injects functional dynamism, and blockchain fortifies cyber-physical trust. The interplay of these vectors suggests that, by 2030, AM could underpin decentralised, on-demand production networks where digital designs flow seamlessly from cloud repositories to heterogeneous printer fleets, monitored and optimised by autonomous agents, powered by recycled or bio-derived feed-stocks, and safeguarded by cryptographic ledgers. Realising this vision will hinge not only on technical ingenuity but also on collaborative governance that aligns industrial incentives with societal goals of sustainability, resilience, and equitable access to advanced manufacturing capabilities.

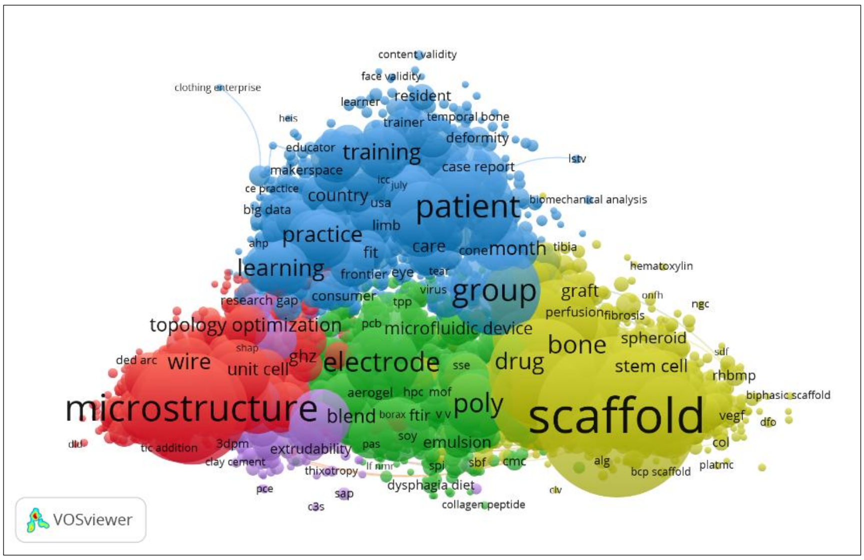

Figure. 1 Bibliometric Analysis of 3D Printing Trends

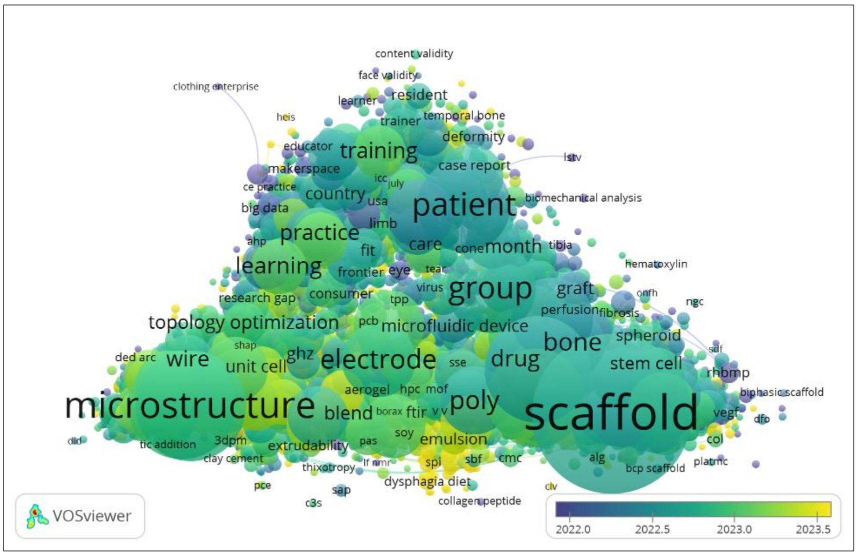

Figure. 2 Overlay of 3D Printing Trends

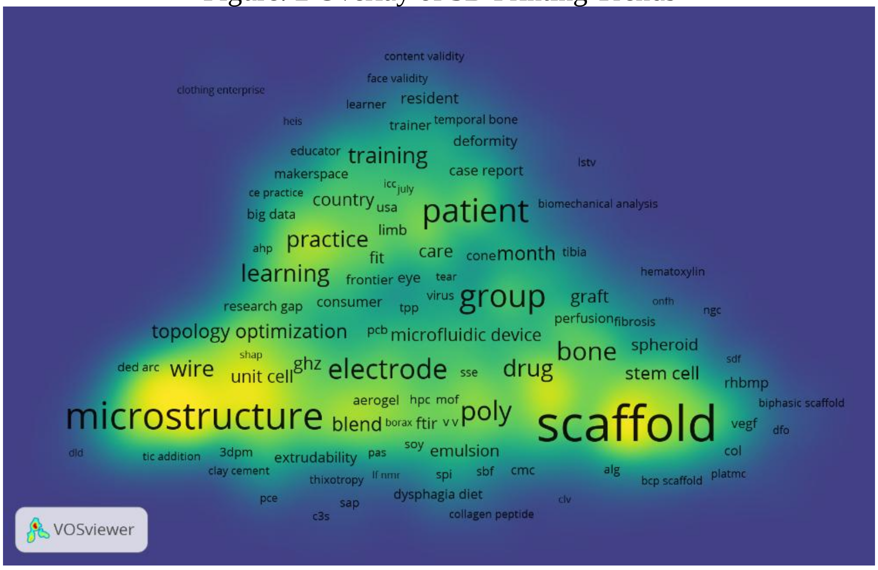

Figure. 3 Density of 3D Printing Trends

The visualization in Figure 1, Figure 2 and Figure 3, generated using VOSviewer, represents a keyword co-occurrence network derived from a bibliometric analysis of literature related to 3D printing (Additive Manufacturing). Each bubble (or node) denotes a keyword or term frequently found in the titles, abstracts, or author keywords of the analyzed publications. The size of each bubble reflects the frequency of the term's occurrence, while the proximity and connecting lines between bubbles indicate the strength of co-occurrence—meaning how often two terms appear together in the same document. Furthermore, colors represent thematic clusters that were automatically detected using a modularity-based clustering algorithm.

The yellow cluster, dominated by the term *scaffold*, represents research in tissue engineering and regenerative medicine. Keywords such as *bone*, *stem cell*, *spheroid*, and *graft* suggest a strong focus on 3D-printed scaffolds for bone regeneration, cell seeding, and bio fabrication. This confirms that bioprinting applications remain a major stream of additive manufacturing research. The blue cluster revolves around the keyword *patient* and includes terms like *training*, *practice*, *learning*, and *resident*. This cluster highlights the use of 3D printing in medical education, simulation training, and patient-specific modeling, indicating that AM is increasingly used to produce anatomical models for surgical planning and hands-on clinical education. In the red cluster, terms such as *microstructure*, *wire*, *topology optimization*, and *DED* *arc* reveal a focus on metal additive manufacturing, particularly wire-based techniques like Directed Energy Deposition (DED) and Wire-Arc AM (WAAM). This research emphasizes the relationship between process parameters, resulting microstructures, and part performance, as well as the use of topology optimization to improve mechanical efficiency. The green cluster includes terms like *electrode*, *microfluidic device*, *poly*, and *emulsion*. This group reflects research on microfluidics, printed electronics, and polymer composites, where 3D printing is used to develop lab-on-chip devices, electrochemical sensors, and multi-phase polymeric materials. The frequent co-occurrence of *poly* with terms from both bio- and material sciences suggests interdisciplinary applications bridging bioprinting and functional device fabrication. The purple cluster is smaller and comprises keywords such as *extrudability*, *thixotropy*, and *clay cement*. This group indicates interest in rheological behavior and printable construction materials, especially for large-scale 3D printing with cementitious and clay-based mixtures.

Overall, this map highlights several key insights. First, *scaffold*, *microstructure*, and *patient* emerge as dominant keywords, confirming that biomedical applications and materials research are central to the current AM landscape. Second, bridging terms like *poly* and *blend* connect clusters, showing growing multidisciplinary collaboration. Third, peripheral keywords such as *clothing enterprise, big data,* or *ghz* suggest emerging or niche research areas that are still underexplored but may gain momentum in the future. Notably, topics such as *sustainability* and *blockchain*, despite their strategic importance in industry discourse, are not prominently represented—indicating either a lack of widespread publication in these areas or the novelty of such topics in academic AM research. Thus, the visualization not only reflects dominant research themes but also reveals underdeveloped areas that may serve as promising frontiers for future investigation.

4. CONCLUSION

The bibliometric analysis of 3D printing literature reveals that additive manufacturing has evolved into a highly multidisciplinary research domain with dominant clusters spanning biomedical engineering, material science, electronics, and education. Central themes such as scaffold, microstructure, and patient reflect a strong emphasis on tissue engineering, material-property optimization, and clinical applications. The consistent presence of terms related to training, microfluidic devices, and electrode fabrication further indicates that 3D printing is no longer confined to prototyping but is now deeply integrated into functional, application-driven research. The clustering structure also illustrates the ecosystem of AM research: the yellow cluster emphasizes the biological and regenerative aspects; the red cluster represents metallic and structural fabrication; the blue cluster underscores human-centered modeling and education; the green cluster highlights micro-device development and multifunctional polymers; and the purple cluster focuses on printable construction materials. These themes collectively signal the convergence of additive manufacturing with bioengineering, electronics, construction, and personalized medicine. However, the map also shows certain limitations. Strategic issues such as sustainability, standardization, and digital trust mechanisms (e.g., blockchain) are underrepresented. Despite their increasing relevance in industrial and policy discourse, these areas appear to remain underexplored in the current academic literature. Additionally, terms related to long-term validation, real-time control systems, and socio-economic impact are either weakly represented or fragmented waste from landfills and natural ecosystems. Economically, this approach empowers local future manufacturing one that is greener, more inclusive, and genuinely sustainable.

5. SUGGESTION

Future studies should give greater attention to emerging but underrepresented topics such as sustainability assessment in AM, circular economy integration, lifecycle analysis, and blockchain-based traceability. These areas are vital for establishing trust, traceability, and environmental accountability in distributed manufacturing. Research in 3D printing is increasingly positioned at the intersection of medicine, materials, data science, and mechanical engineering. Collaborative projects that bridge these disciplines—such as AI-enabled bioprinting or smart scaffolds with embedded electronics—should be encouraged to accelerate innovation and address complex challenges. To improve model transferability and comparability in AI applications for AM, there is a critical need for large, standardized, and publicly available datasets. This will support reproducibility and drive the development of explainable AI and real-time process monitoring tools. Many concepts demonstrated in academic settings, especially in 4D printing and micro structured scaffolds, require scale-up and regulatory readiness before reaching real-world use. Research funding and incentives should focus on technology transfer, industrial prototyping, and performance benchmarking. The significant presence of keywords related to *training* and *resident* suggests the growing role of 3D printing in education and simulation. Future efforts should involve the design of standardized curricula and evaluation frameworks for medical and engineering training using AM-generated tools.

REFERENCES

[1] S. Ali, M. J. Prajapati, C. Bhat, C.-P. Jiang, and J.-Y. Jeng, "Additive manufactured enabled digital metallurgy processes, challenges and future prospects," *Appl Mater Today*, vol. 42, 2025, doi: 10.1016/j.apmt.2024.102580.

[2] G. Xiong *et al.*, "TrajSGAN: A Semantic-Guiding Adversarial Network for Urban Trajectory Generation," *IEEE Trans Comput Soc Syst*, vol. 11, no. 2, pp. 1733–1743, 2024, doi: 10.1109/TCSS.2023.3235923.

[3] A. Aït-Kaddour *et al.*, "Transforming plant-based waste and by-products into valuable products using various 'Food Industry 4.0' enabling technologies: A literature review," *Science of the Total Environment*, vol. 955, 2024, doi: 10.1016/j.scitotenv.2024.176872.

[4] J. A. Kanko, A. P. Sibley, and J. M. Fraser, "In situ morphology-based defect detection of selective laser melting through inline coherent imaging," *J Mater Process Technol*, vol. 231, pp. 488–500, 2016, doi: 10.1016/j.jmatprotec.2015.12.024.

[5] X.-Q. Han *et al.*, "AI-Driven Inverse Design of Materials: Past, Present, and Future," *Chinese Physics Letters*, vol. 42, no. 2, 2025, doi: 10.1088/0256-307X/42/2/027403.

[6] Y. Wu *et al.*, "Polymer-induced self-assembly strategy toward 3D printable porous MoO3/Al2O3 catalyst for efficient oxidative desulfurization," *J Colloid Interface Sci*, vol. 686, pp. 14–26, 2025, doi: 10.1016/j.jcis.2025.01.140.

[7] G. L. Smith *et al.*, "3D-Printed Multi-scale Fluidics for Liquid Metals," *Adv Mater Technol*, vol. 9, no. 14, 2024, doi: 10.1002/admt.202301980.

[8] S. Bhandari *et al.*, "Material-extrusion based additive manufacturing of BaTiO3 ceramics: from filament production to sintered properties," *Addit Manuf*, vol. 88, 2024, doi: 10.1016/j.addma.2024.104238.

[9] W. Crupano, B. Adrover-Monserrat, J. Llumà, R. Jerez-Mesa, and J. A. Travieso-Rodriguez, "Investigating mechanical properties of 3D printed polylactic acid / poly-3-hydroxybutyrate composites. Compressive and fatigue performance," *Heliyon*, vol. 10, no. 18, 2024, doi: 10.1016/j.heliyon.2024.e38066.

[10] W. Gao, M. Wang, and H. Bai, “A review of multifunctional nacre-mimetic materials based on bidirectional freeze casting,” *J Mech Behav Biomed Mater*, vol. 109, 2020, doi: 10.1016/j.jmbbm.2020.103820.

[11] H. Yang, N. D’Ambrosio, P. Liu, D. Pasini, and L. Ma, “Shape memory mechanical metamaterials,” *Materials Today*, vol. 66, pp. 36–49, 2023, doi: 10.1016/j.mattod.2023.04.003.

[12] P. Sreeramagiri, A. Bhagavatam, A. Ramakrishnan, H. Alrehaili, and G. P. Dinda, “Design and development of a high-performance Ni-based superalloy WSU 150 for additive manufacturing,” *J Mater Sci Technol*, vol. 47, pp. 20–28, 2020, doi: 10.1016/j.jmst.2020.01.041.

[13] A. Boretti, “A techno-economic perspective on 3D printing for aerospace propulsion,” *J Manuf Process*, vol. 109, pp. 607–614, 2024, doi: 10.1016/j.jmapro.2023.12.044.

[14] O. Lkadi, S. Abouhazim, M. Nassraoui, and O. Bouksour, “A comprehensive design framework for additive manufacturing in the automotive industry: a case study,” *Archives of Materials Science and Engineering*, vol. 125, no. 1, pp. 32–41, 2024, doi: 10.5604/01.3001.0054.4610.

[15] J. Hussan K S *et al.*, “Fabrication and challenges of 3D printed sensors for biomedical applications-Comprehensive review,” *Results in Engineering*, vol. 21, 2024, doi: 10.1016/j.rineng.2024.101867.

[16] S. Raja *et al.*, “Energy-efficient FDM printing of sustainable polymers: Optimization strategies for material and process performance,” *Applied Chemical Engineering*, vol. 7, no. 3, 2024, doi: 10.59429/ace.v7i3.5537.

[17] B. S. Qurraie, S. M. Top, E. B. Özeren, and Ö. Özeren, “Bibliometric Analysis of 3D Printing Technology in the Field of Architecture: An Education Review,” *International Journal of Design Management and Professional Practice*, vol. 18, no. 2, pp. 125–145, 2024, doi: 10.18848/2325-162X/CGP/v18i02/125-145.

[18] M. Jesus, J. Teixeira, A. S. Guimarães, B. Rangel, and J. L. Alves, “From 3D survey data of cultural heritage artefacts to 3D-printed prototypes based on cement and lime-based mortars,” *Digital Applications in Archaeology and Cultural Heritage*, vol. 37, 2025, doi: 10.1016/j.daach.2025.e00412.

[19] N. Ay and M. Bozdemir, “Conceptual Design Process of a Missile Model and Production Using Additive Manufacturing Method,” *Def Sci J*, vol. 74, no. 5, pp. 734–742, 2024, doi: 10.14429/dsj.74.19512.

[20] G. Marchese *et al.*, “The influence of the process parameters on the densification and microstructure development of laser powder bed fused inconel 939,” *Metals (Basel)*, vol. 10, no. 7, pp. 1–19, 2020, doi: 10.3390/met10070882.

[21] E. M. Jacobson, I. T. Cummings, P. H. Fickenwirth, E. B. Flynn, and A. J. Wachtor, “Using Steady-State Ultrasonic Direct-Part Measurements for Defect Detection in Additively Manufactured Metal Parts,” in *Conference Proceedings of the Society for Experimental Mechanics Series*, E. D.S., Ed., Los Alamos National Laboratory, Engineering Institute, Los Alamos, NM, United States: Springer, 2022, pp. 59–73. doi: 10.1007/978-3-030-75914-8_7.

[22] H. T. Tazwar, M. F. Antora, I. Nowroj, and A. B. Rashid, “Conductive polymer composites in soft robotics, flexible sensors and energy storage: Fabrication, applications and challenges,” *Biosens Bioelectron X*, vol. 24, 2025, doi: 10.1016/j.biosx.2025.100597.

[23] S. F. Nogueira *et al.*, “Design and development of a cost-effective buoy using 3D printing for coastal monitoring,” *HardwareX*, vol. 22, 2025, doi: 10.1016/j.ohx.2025.e00657.

[24] J. Li *et al.*, “MedShapeNet - a large-scale dataset of 3D medical shapes for computer vision,” *Biomedizinische Technik*, vol. 70, no. 1, pp. 71–90, 2025, doi: 10.1515/bmt-2024-0396.

[25] C.-C. Huang *et al.*, “Novel design of additive manufactured hollow porous implants,” *Dental Materials*, vol. 36, no. 11, pp. 1437–1451, 2020, doi: 10.1016/j.dental.2020.08.011.

[26] R. Durga Prasad Reddy and V. Sharma, “Additive manufacturing in drug delivery applications: A review,” *Int J Pharm*, vol. 589, 2020, doi: 10.1016/j.ijpharm.2020.119820.

[27] C. Y. Zhu, J. N. Pires, and A. Azar, “A novel multi-brand robotic software interface for industrial additive manufacturing cells,” *Industrial Robot*, vol. 47, no. 4, pp. 581–592, 2020, doi: 10.1108/IR-11-2019-0237.

[28] I. Zarkesh *et al.*, “Scalable and cost-effective generation of osteogenic micro-tissues through the incorporation of inorganic microparticles within mesenchymal stem cell spheroids,” *Biofabrication*, vol. 12, no. 1, 2020, doi: 10.1088/1758-5090/ab51ae.

[29] M. Karuppusamy, R. Thirumalaisamy, S. Palanisamy, S. Nagamalai, E. El Sayed Massoud, and N. Ayrilmis, “A review of machine learning applications in polymer composites: advancements, challenges, and future prospects,” *J Mater Chem A Mater*, 2025, doi: 10.1039/d5ta00982k.

[30] M. Elbadawi, H. Li, S. Sun, M. E. Alkahtani, A. W. Basit, and S. Gaisford, “Artificial intelligence generates novel 3D printing formulations,” *Appl Mater Today*, vol. 36, 2024, doi: 10.1016/j.apmt.2024.102061.

[31] E. Westphal and H. Seitz, “Generative Artificial Intelligence: Analyzing Its Future Applications in Additive Manufacturing,” *Big Data and Cognitive Computing*, vol. 8, no. 7, 2024, doi: 10.3390/bdcc8070074.

[32] Y. Jiang, A. X. Serrano, W. Choi, R. C. Advincula, and H. F. Wu, “Advanced and functional composite materials via additive manufacturing: Trends and perspectives,” *MRS Commun*, vol. 14, no. 4, pp. 449–459, 2024, doi: 10.1557/s43579-024-00625-5.

[33] E. Blanzeanu *et al.*, “Chitosan-polylactic acid composites: from seafood waste to advanced functional materials for 3D printing,” *Adv Compos Hybrid Mater*, vol. 8, no. 1, 2025, doi: 10.1007/s42114-024-01131-x.

[34] Y. Jin and J. Liu, “4D Printing: Research Focuses and Prospects,” *Designs (Basel)*, vol. 8, no. 6, 2024, doi: 10.3390/designs8060106.

[35] B. Bakkal, K. G. Topsakal, and G. S. Duran, “New horizons in dentistry and orthodontics with 4D printing technologies 4D printing and orthodontics,” *Australasian Orthodontic Journal*, vol. 41, no. 1, pp. 32–39, 2025, doi: 10.2478/aoj-2025-0003.

[36] T. Li, Z. Huang, G. C.-P. Tsui, C.-Y. Tang, and Y. Deng, “Recent advances in 4D printing of hydrogels,” *Reviews on Advanced Materials Science*, vol. 63, no. 1, 2024, doi: 10.1515/rams-2024-0028.

[37] L. Deng, S. Li, and Y. Zhu, “The Influence of Blockchain on Intellectual Property Pledge Financing Decisions in 3D Printing Technology,” *IEEE Access*, vol. 13, pp. 41797–41821, 2025, doi: 10.1109/ACCESS.2025.3541119.

[38] G. Sadurya and J. K. Selvaranee, "Redefining Supply Chain Practices in the Textile Industry – Sustainable Development through Blockchain Technology," *Textile and Leather Review*, vol. 8, pp. 273–303, 2025, doi: 10.31881/TLR.2025.008.

[39] M. Mozaffar *et al.*, "Mechanistic artificial intelligence (mechanistic-AI) for modeling, design, and control of advanced manufacturing processes: Current state and perspectives," *J Mater Process Technol*, vol. 302, 2022, doi: 10.1016/j.jmatprotec.2021.117485.

[40] Z. Zhang, X. Zhou, Y. Fang, Z. Xiong, and T. Zhang, "AI-driven 3D bioprinting for regenerative medicine: From bench to bedside," *Bioact Mater*, vol. 45, pp. 201–230, 2025, doi: 10.1016/j.bioactmat.2024.11.021.

[41] P. Singh *et al.*, "3D-printed cellulose nanocrystals and gelatin scaffolds with bioactive cues for regenerative medicine: Advancing biomedical applications," *Int J Biol Macromol*, vol. 278, 2024, doi: 10.1016/j.ijbiomac.2024.134402.

[42] F. Li *et al.*, "Progress of AI assisted synthesis of polysaccharides-based hydrogel and their applications in biomedical field," *Int J Biol Macromol*, vol. 287, 2025, doi: 10.1016/j.ijbiomac.2024.138643.

[43] A. O. Inoma, O. O. Ibhadode, and A. A. O. Ibhadode, "The perception and deployment of 3D printing in the Nigerian educational sector for science and engineering programs," *Sci Afr*, vol. 10, 2020, doi: 10.1016/j.sciaf.2020.e00641.

[44] R. Agrawal and V. S, "Sustainability evaluation of additive manufacturing processes using grey-based approach," *Grey Systems*, vol. 10, no. 4, pp. 393–412, 2020, doi: 10.1108/GS-08-2019-0028.

[45] V. Vijayenthiran, B. A. K. S. Perera, and A. S. Kavirathna, "Convergence of 3D printing with circular economy to improve the construction sustainability," *Smart and Sustainable Built Environment*, 2025, doi: 10.1108/SASBE-09-2024-0397.

[46] C. Roux, J. Archez, C. Le Gall, M. Saadé, A. Féraille, and J.-F. Caron, "Towards Sustainable Material: Optimizing Geopolymer Mortar Formulations for 3D Printing: A Life Cycle Assessment Approach," *Sustainability (Switzerland)*, vol. 16, no. 8, 2024, doi: 10.3390/su16083328.

[47] K. DePalma, M. R. Walluk, A. Murtaugh, J. Hilton, S. McConky, and B. Hilton, "Assessment of 3D printing using fused deposition modeling and selective laser sintering for a circular economy," *J Clean Prod*, vol. 264, 2020, doi: 10.1016/j.jclepro.2020.121567.

[48] A. Islam, J. Hasan, and K. R. Hossain, "Intelligent materials in 3D printing: A journey from additive manufacturing to 4D printing," *Journal of Advanced Manufacturing Science and Technology*, vol. 4, no. 4, 2024, doi: 10.51393/j.jamst.2024016.

[49] P. Kumar, P. Suryavanshi, S. Kumar Dwivedy, and S. Banerjee, "Stimuli-responsive materials for 4D Printing: Mechanical, Manufacturing, and Biomedical Applications," *J Mol Liq*, vol. 410, 2024, doi: 10.1016/j.molliq.2024.125553.

[50] J. Stuckner, S. M. Taheri-Mousavi, and J. E. Saal, "ARTIFICIAL INTELLIGENCE AND MACHINE LEARNING IN MATERIALS SCIENCE," *Advanced Materials and Processes*, vol. 182, no. 4, pp. 14–20, 2024, doi: 10.31399/asm.amp.2024-04.p014.

[51] I. Rojek, T. Marciniak, and D. Mikołajewski, "Digital Twins in 3D Printing Processes Using Artificial Intelligence," *Electronics (Switzerland)*, vol. 13, no. 17, 2024, doi: 10.3390/electronics13173550.

[52] A. Sachan, H. S. Grover, and N. M. A. Krishnan, “Leveraging artificial intelligence for advanced glass science and discovery,” *American Ceramic Society Bulletin*, vol. 103, no. 6, pp. 30–34, 2024, [Online]. Available: https://www.scopus.com/inward/record.uri?eid=2-s2.0-85200647929&partnerID=40&md5=3178bc06ea447e1aa69ce7aba52573cc

[53] M. Najeeb and S. Islam, “Artificial intelligence (AI) in restorative dentistry: current trends and future prospects,” *BMC Oral Health*, vol. 25, no. 1, 2025, doi: 10.1186/s12903-025-05989-1.

[54] P. Karmiris-Obratański, E. L. Papazoglou, N. E. Karkalos, and A. P. Markopoulos, “Volume energy density and laser power: key determinants in SLS-processed PA12 mechanical properties,” *International Journal of Advanced Manufacturing Technology*, vol. 130, no. 5–6, pp. 2505–2522, 2024, doi: 10.1007/s00170-023-12806-y.

[55] A. A. Salim, H. Bakhtiar, S. K. Ghoshal, and M. S. A. Aziz, “3D-printed titanium-aluminum-vanadium alloy produced at various laser powers: evaluation of microstructures and mechanical characteristics,” *International Journal of Advanced Manufacturing Technology*, vol. 132, no. 7–8, pp. 3671–3681, 2024, doi: 10.1007/s00170-024-13616-6.

[56] J. Chen *et al.*, “Laser-based powder bed fusion of nickel-based superalloy designed specifically for turbine blades using high-power flat-top laser: Towards high-speed manufacturing and directional solidification,” *J Alloys Compd*, vol. 1022, 2025, doi: 10.1016/j.jallcom.2025.179902.

[57] F. Sun and J. Han, “Impact of Laser Power on Electrochemical Performance of CeO2/Al6061 Alloy Through Selective Laser Melting (SLM),” *Crystals (Basel)*, vol. 15, no. 1, 2025, doi: 10.3390/cryst15010084.

[58] X. Kong *et al.*, “Effect of scanning speeds on mechanical properties of CoCrNi medium entropy alloy prepared by laser additive manufacturing,” *Heliyon*, vol. 10, no. 1, 2024, doi: 10.1016/j.heliyon.2023.e23850.

[59] R. Ismail *et al.*, “Investigation of the Effect of Nozzle Temperature in Fused Deposition Modelling on the Mechanical Properties and Degradation Behaviour of 3D-Printed PLA/PCL/HA Biocomposite Filaments,” *Journal of Advanced Research in Applied Mechanics*, vol. 135, no. 1, pp. 83–96, 2025, doi: 10.37934/aram.135.1.8396.

[60] A. Saxena, G. Manogharan, and C. Rahn, “Adaptive stiffness structures via additively manufactured fluid accumulators,” *Smart Mater Struct*, vol. 34, no. 1, 2025, doi: 10.1088/1361-665X/ada09b.

[61] V. Furlan, F. Insero, and H. Giberti, “Robotic FDM for free-form fabrication: evaluating adaptive non-planar slicing with different contour methods,” *Rapid Prototyp J*, vol. 31, no. 11, pp. 160–178, 2025, doi: 10.1108/RPJ-03-2024-0109.

[62] M. Zmyślony, K. Dradrach, and J. S. Biggins, “Slicing vector fields into tool paths for additive manufacturing of nematic elastomers,” *Addit Manuf*, vol. 97, 2025, doi: 10.1016/j.addma.2024.104604.

[63] J. Mikula *et al.*, “The role of tool path on microstructure uniformity in large-format additive manufacturing: integrated thermo-metallurgical-mechanical approach,” *Int J Comput Integr Manuf*, vol. 38, no. 1, pp. 40–61, 2025, doi: 10.1080/0951192X.2024.2314783.

[64] X. Li *et al.*, “Revealing effects of powder reuse for LPBF-fabricated NiTi shape memory alloys,” *Front Mater Sci*, vol. 18, no. 4, 2024, doi: 10.1007/s11706-024-0697-5.

[65] C. İ. Çalışkan and Ü. Arpacıoğlu, "Additive manufacturing: a new design approach-LPBF design and production flow chart algorithm," *Progress in Additive Manufacturing*, 2024, doi: 10.1007/s40964-024-00878-5.

[66] S. Negi, P. Bhargava, and P. S. Gandhi, "Thin alumina wafer fabrication by vat photopolymerisation based additive manufacturing," *Ceram Int*, vol. 51, no. 3, pp. 2891–2897, 2025, doi: 10.1016/j.ceramint.2024.11.266.

[67] C. Lüthi, M. Bambach, and M. Afrasiabi, "MULTI-3: A GPU-enhanced meshfree simulation framework for multi-track, multi-layer, and multi-material laser powder bed fusion processes," *J Manuf Process*, vol. 147, pp. 29–48, 2025, doi: 10.1016/j.jmapro.2025.04.087.

[68] M. Selim Ahmed, R. Hodgir, S. Mujumdar, and R. Singh, "Computational modeling of multi-track multi-layer laser directed energy deposition process," *Manuf Lett*, vol. 41, pp. 983–991, 2024, doi: 10.1016/j.mfglet.2024.09.122.

[69] G. Zyla and M. Farsari, "Frontiers of Laser-Based 3D Printing: A Perspective on Multi-Photon Lithography," *Laser Photon Rev*, vol. 18, no. 7, 2024, doi: 10.1002/lpor.202301312.