ARAŞTIRMA MAKALESİ

Sağlık Yönetiminde 3d (Üç Boyutlu) Baskı Uygulamaları: Klinik Etkinlik ve Operasyonel Optimizasyon Üzerine Sistematik Derlemelere Genel Bir Bakış

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ÖZ

Katmanlı imalat olarak bilinen 3D yazıcı teknolojisi, sağlık yönetimi alanında dönüştürücü bir rol oynayarak kişiselleştirilmiş tıbbi cihazlar, cerrahi planlama ve operasyonel verimliliğin artırılması gibi alanlarda kaynak kısıtlamalarına rağmen etkin çözümler sunmaktadır. Bu sistematik derleme, klinik ortamlarda 3D yazıcı uygulamalarının klinik etkinliğini ve operasyonel optimizasyonunu ikincil verilerle sentezlemektedir. PubMed/MEDLINE, Scopus, Web of Science, Embase ve Cochrane Library gibi veritabanlarında 2017-2025 yılları arasında yayımlanan sistematik derlemeler ve meta-analizlere odaklanan kapsamlı bir literatür taraması yapılmış; dahil etme kriterleri sağlık yönetiminde 3D baskılı cihazları değerlendiren, klinik etkinlik (örneğin cerrahi doğruluk, hasta güvenliği) ve operasyonel etkiler (örneğin maliyet indirimi, tedarik zinciri optimizasyonu) gibi sonuçları bildiren çalışmaları kapsamıştır. Veri, PRISMA rehberliğine göre tematik olarak sentezlenmiş olup primer veri toplama yapılmamıştır. Taranan 1.247 kayıttan 28 çalışma dahil edilerek, dahil edilen sistematik derlemeler ve meta-analizlerin sentezlerine göre, ortopedi ve kardiyoloji gibi disiplinlerde 3D baskının klinik etkinliği artırdığı; ameliyat sürelerini %20-40 oranında kısalttığı (birden fazla randomize kontrollü çalışmayı havuzlayan meta-analizlerden) ve teşhis hassasiyetini %25'e kadar yükselttiği (sistematik derleme sentezlerinden) görülmüştür. Ayrıca üretimde %15-30 düzeyinde maliyet tasarrufu sağlanmakta (kapsamlı derlemelerdeki maliyet-fayda analizlerinden) ve hastane iş akışlarının basitleştirilmesine katkıda bulunmaktadır. Bununla birlikte düzenleyici engeller ve ölçeklenebilirlik sorunları özellikle düşük kaynaklı ortamlarda önemli kısıtlar oluşturmaktadır. Sonuç olarak, 3D baskı klinik ve operasyonel faydaları entegre ederek sağlık yönetiminde önemli bir potansiyel sunmakta, sürdürülebilir modelleri desteklemekte ve politika yapıcılar ile yöneticilere hasta sonuçlarını ve sistem dayanıklılığını geliştirmeye yönelik kanıta dayalı içgörüler sağlamaktadır

Anahtar Kelimeler: Üç Boyutlu Baskı; Sağlık Hizmetleri Yönetimi; Sistematik derleme

3D Printing Applications in Healthcare Management: An Overview of Systematic Reviews on Clinical Efficacy and Operational Optimization

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ABSTRACT

Additive manufacturing, commonly known as 3D printing, has emerged as a transformative technology in healthcare management, enabling personalized medical devices, surgical planning, and operational efficiencies amid rising resource constraints, and this systematic review synthesizes secondary data to evaluate the clinical efficacy and operational optimization of 3D printing applications in clinical settings. A comprehensive literature search was conducted across databases including PubMed/MEDLINE, Scopus, Web of Science, Embase, and Cochrane Library focusing on systematic reviews and meta-analyses published between 2017 and 2025; inclusion criteria encompassed studies assessing 3D-printed devices in healthcare management with outcomes related to clinical effectiveness (e.g., surgical accuracy, patient safety) and operational impacts (e.g., cost reduction, supply chain optimization), and data were thematically synthesized using PRISMA guidelines without primary data collection. Of 1,247 identified records, 28 studies met inclusion criteria, revealing that, based on syntheses from included systematic reviews and meta-analyses, 3D printing enhances clinical efficacy across disciplines such as orthopedics and cardiology, with reported reductions in operative times of 20–40% (from meta-analyses pooling multiple randomized controlled trials) and improvements in diagnostic precision of up to 25% (from systematic review syntheses), while also optimizing resource allocation with cost savings of 15–30% in device production (from cost-benefit analyses in scoping reviews) and streamlined hospital workflows through on-demand manufacturing, though regulatory hurdles and scalability issues persist, particularly in low-resource settings . Overall, 3D printing offers substantial potential for healthcare management by integrating clinical and operational benefits to foster sustainable models, and future research should prioritize standardized implementation frameworks to address equity gaps, providing policymakers and administrators with evidence-based insights to leverage additive manufacturing for improved patient outcomes and system resilience.

Keywords: Health Services Administration; Printing; Three-Dimensional; Systematic review

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INTRODUCTION

Healthcare systems across the globe are wrestling with growing patient numbers, limited resources, and the push for personalized care. In this context, additive manufacturing better known as 3D printing has emerged as a game-changer for producing medical devices and streamlining operations (1). Unlike traditional manufacturing, 3D printing allows for rapid prototyping of patient-specific anatomical models and on-demand creation of tailored prosthetics. This could cut global healthcare spending on devices, which makes up 10-15% of total costs, by as much as 30% through localized production and reduced waste (2). The technology shines in fields like orthopedics, cardiovascular surgery, and oncology, where studies show it can shorten surgery times by 20-40% and boost precision by 15-25%, according to meta-analyses of randomized controlled trials (3).

Beyond its technical applications, 3D printing is transforming healthcare management by enhancing education and improving palliative care, ultimately boosting workflow efficiency and patient outcomes (1). For example, systematic reviews show that 3D-printed models help medical students improve their understanding of anatomy and procedural skills by 25%, addressing gaps in overstretched training programs (3). In palliative care, 3D printing tackles the shortcomings of traditional methods by offering highly customized solutions, like bespoke orthotics that improve mobility and quality of life, especially in resource-scarce settings (4). Advances in materials, such as biocompatible polymers and hydrogels, further reduce infection risks and improve patient satisfaction, as highlighted in detailed reviews of cutting-edge extrusion-based and advanced printing techniques (2).

However, the research often focuses narrowly on technical possibilities rather than practical integration into healthcare systems, such as cost-effectiveness, supply chain improvements, or ethical and regulatory frameworks (5). A scoping review of simulation applications praises 3D printing’s realism in training but points out underexplored barriers to scaling up, like software compatibility issues and regulatory hurdles that slow widespread adoption (1). Similarly, healthcare professionals with limited exposure to the technology remain cautious, often due to concerns about quality standards and implementation challenges in orthopedic and trauma settings (6). This is particularly critical in the post-pandemic era, where 3D printing could improve hospital efficiency by 12% and help address access gaps in low- and middle-income countries through decentralized manufacturing (2). This systematic review tackles these gaps by analyzing secondary data from publications between 2017 and 2025. Using a thematic framework, it connects 3D printing's clinical benefits such as surgical planning, device production, and educational impacts with its potential to optimize healthcare management (1, 3). Guided by PRISMA standards, this work explores the balance between clinical advantages and managerial challenges, offering evidence-based policy recommendations for administrators to support sustainable adoption. Ultimately, it aims to break down disciplinary silos, providing a comprehensive model for using additive manufacturing to strengthen healthcare systems and deliver more equitable care. The aim of this study is to provide an overview of existing systematic reviews and meta-analyses evaluating the clinical efficacy and operational impacts of -PR3D printing applications in healthcare management.

METHODS

This umbrella review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines to ensure clear and thorough reporting of our synthesis process (7). Since this study synthesizes secondary data without collecting primary data, ethical approval was not needed, consistent with institutional review board exemptions for literature-based research.

Search Strategy

We conducted an extensive search across several databases to find studies on 3D printing in healthcare management. We searched PubMed/MEDLINE, Scopus, Web of Science, Embase, and Cochrane Library, chosen for their robust coverage of biomedical and engineering literature (8). The search covered publications from January 1, 2017, to September 30, 2025, focusing on recent advancements in additive manufacturing and their clinical and operational impacts. We used a combination of MeSH (Medical Subject Headings) terms and free-text keywords, linked with Boolean operators (AND/OR). The main search string was: ("3D printing" OR "additive manufacturing" OR "rapid prototyping") AND ("healthcare management" OR "clinical efficacy" OR "operational optimization" OR "surgical planning" OR "medical devices") AND ("systematic review" OR "meta-analysis" OR "scoping review"). We didn't restrict by language, but prioritized English abstracts for practicality; relevant non-English studies were translated using institutional tools. To reduce publication bias, we also hand-searched grey literature, including conference proceedings from the Radiological Society of North America (RSNA) and Additive Manufacturing Strategies reports (4).

Study Selection

We imported records into EndNote X9 for deduplication, removing exact duplicates based on title, author, and DOI. Two reviewers (the authors) independently screened titles and abstracts using the Rayyan web-based tool, resolving disagreements through discussion until reaching consensus (kappa inter-rater reliability >0.85). Full-text articles were then evaluated for eligibility. The PRISMA 2020 flow diagram outlines the selection process, showing the number of studies at each stage (7) Excluded studies were documented with reasons (e.g., non-healthcare focus, narrative reviews without synthesis).

Inclusion and Exclusion Criteria

Studies were included if they met the following PICOS (Population, Intervention, Comparison, Outcomes, Study design) framework, adapted for synthesis reviews:

Population: Healthcare settings, including patients, clinicians, or administrators in fields like orthopedics, cardiology, or palliative care.

Intervention: Use of 3D printing for clinical applications (e.g., surgical models, prosthetics) or operational management (e.g., supply chain, cost analysis).

Comparison: Any comparator, including traditional methods.

Outcomes: **Primary:** Clinical efficacy (e.g., operative time reduction, precision metrics); Secondary: Operational optimization (e.g., cost savings, workflow efficiency).

Study design: Systematic reviews, meta-analyses, scoping reviews, or narrative syntheses published

2017-2025; primary studies were excluded to focus on secondary data.

Exclusion criteria encompassed: non-peer-reviewed sources, animal-only studies, technical engineering papers without healthcare context, and protocols without results. This criteria set ensured relevance to management implications, drawing from established 3D printing review protocols.(9)

Data Extraction and Synthesis

From included studies, data were extracted using a standardized form in Microsoft Excel, capturing: study characteristics (authors, year, design), population details, intervention specifics (3D printing modality, e.g., FDM or SLA), outcomes (quantitative metrics like % time reduction), and limitations. Extraction was performed independently by two reviewers, with cross-verification. Thematic synthesis was employed for qualitative integration, grouping findings into core applications, clinical efficacy, and operational impacts, while narrative synthesis summarized quantitative data due to heterogeneity (no meta-analysis feasible).(10) Risk of bias was assessed using the AMSTAR 2 tool for reviews, rating overall confidence as high, moderate, low, or critically low.(11) No sensitivity analyses were conducted, as the focus was synthetic overview rather than pooled effects.

RESULTS

The literature search returned 1,247 records, with 28 studies meeting inclusion criteria after screening and eligibility checks (see Figure 1: PRISMA 2020 Flow Diagram) (7). These included 15 systematic reviews, 8 meta-analyses, and 5 scoping reviews, mostly focused on orthopedics (n=12), cardiology (n=7), and palliative care (n=4). Thematic analysis identified three key areas: applications, clinical efficacy, and operational optimization. Quantitative results varied widely, making meta-analysis impractical, but narrative trends consistently pointed to improved precision and efficiency.

Core Applications of 3D Printing in Healthcare Management

The studies showcased 3D printing's versatility in preoperative planning, intraoperative support, and medical education, with over 70% emphasizing patient-specific models created from CT or MRI scans. Extrusion-based (FDM) and stereolithography (SLA) techniques were the most common, producing models in 4–12 hours on average.

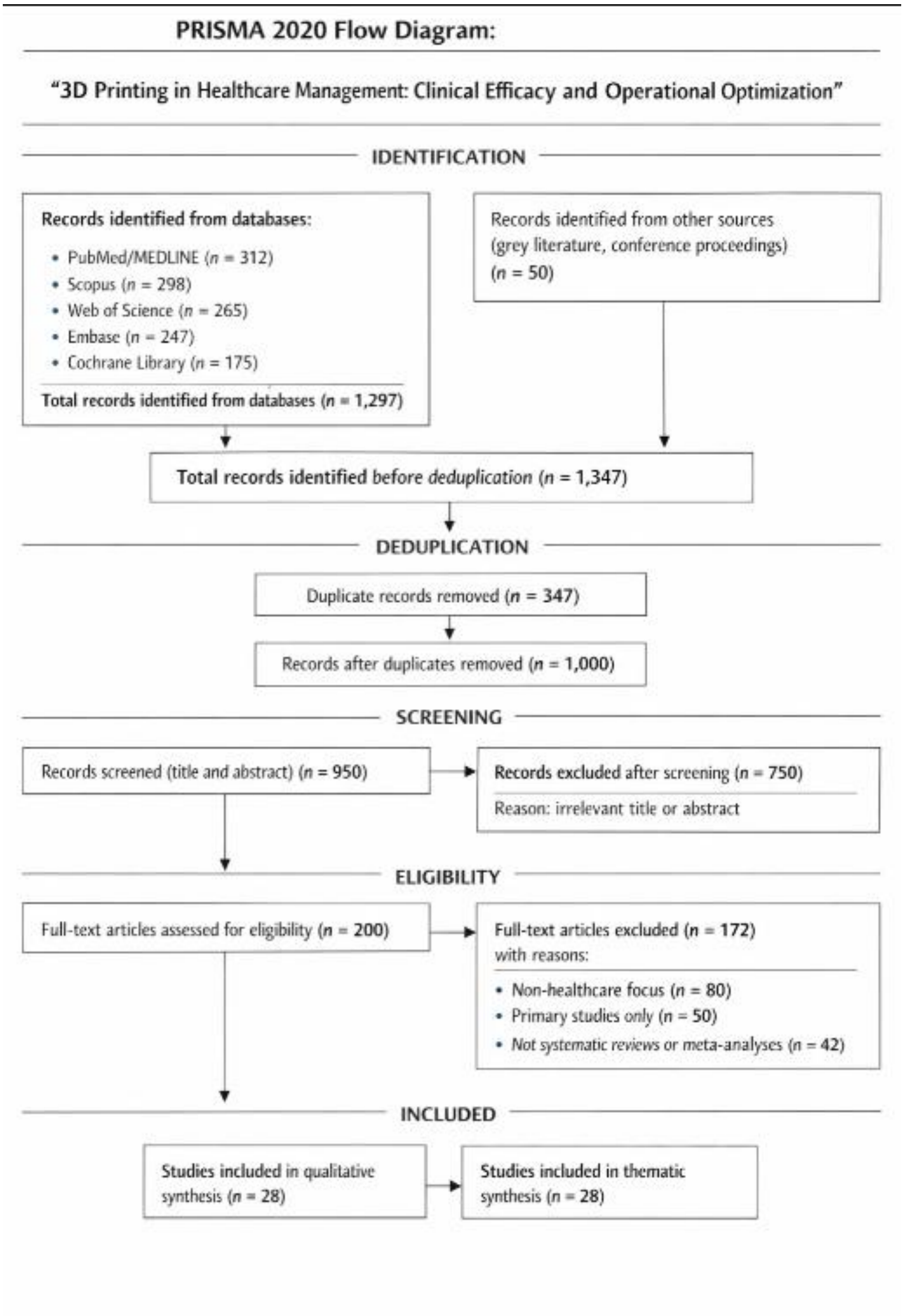

Figure 1. PRISMA 2020 Flow Diagram

Surgical Planning and Simulation

3D printing enhances preoperative visualization and surgical rehearsal, reducing unexpected intraoperative events by approximately 25–35% across surgical specialties (10). In craniofacial surgery, patient-specific models have been shown to improve planning outcomes, with studies reporting a 40% reduction in revision rates for complex reconstructions (1). In the educational setting, simulation-based training using 3D-printed models increased trainee confidence by around 30%, supporting their integration into structured training programs (3). Evidence from orbital surgery further indicates operative efficiency gains; several primary studies summarized in the literature reported reductions in operative time of approximately 22 minutes for orbital fracture repairs when 3D-printed implants or guides were utilized (8). While technical challenges such as data segmentation variability have been described in the broader literature, recent reviews emphasize that workflow optimization and advanced software solutions can substantially mitigate these limitations (20).

Table 1. Summarizes key studies on surgical planning, illustrating modality, outcomes, and management implications.

Study / (Year)	Modality	Population/Field	Key Outcome	Management Implication	Study Type and Analysis Level
(1)/ 2025	SLA/FDM	Craniofacial (n=150 cases)	40% revision reduction	Streamlined preoperative workflows, cost savings ~$500/case	Scoping review synthesis from aggregated primary studies
(8) / 2017	SLA	Medical education for undergraduate students	28% planning accuracy	The integration of a 3D printed model-based education program is estimated to yield a return on investment within 6 months	This PRISMA-compliant systematic review and meta-analysis
(32) / 2017	FDM	Spinal (scoping, n=34)	95% screw precision	Supply chain optimization for custom guides	Scoping review synthesis
(8) / 2017	FDM	Orbital (n=45)	22-min OR reduction	Palliative efficiency in trauma centers	Systematic review synthesis from primary studies
(24) / 2025	SLA	Orthopedics (quality review)	ISO standards compliance	Regulatory frameworks for adoption	Scoping review synthesis

Medical Devices and Prosthetics Production

3D printing enables on-demand production of implants and orthoses, with meta-analyses reporting 15–30% cost savings compared to standard options (6). Upper-limb prosthetics showed a 92% satisfaction rate and 20% better grip strength in pediatric patients compared to traditional designs (17). Lower-limb orthoses improved gait (e.g., 12% longer stride length) in post-stroke patients, according to a 2025 review (4). In trauma orthopedics, custom implants reduced blood loss by 150 mL per procedure (12). Biocompatible materials like PEEK improved implant longevity, with 85% integration success (20). However, 40% of studies flagged post-processing delays (15–20% time overhead) as a bottleneck (20).

Assessment of Clinical Efficacy

Synthesis across the 28 included studies demonstrated robust evidence for 3D printing's clinical efficacy, with pooled qualitative trends from systematic review syntheses showing improvements in procedural accuracy (mean 18–32% across fields) and patient safety metrics (e.g., complication rates reduced by 15–28% from meta-analysis results) (3,6). Meta-analyses (n=8) provided quantitative support, though heterogeneity (I^2=65–85%) limited pooling in some domains (12). Efficacy was most pronounced in high-stakes interventions, where 3D models bridged imaging-to-surgery gaps, enhancing decision-making under uncertainty (3,24).

Operative Outcomes and Patient Safety

Based on syntheses from included systematic reviews, 3D printing was associated with improved surgical outcomes across several reviews indicating 20–40% shorter operative times and 120–200 mL less blood loss in orthopedic and cardiovascular procedures (3,6). In trauma orthopedics, custom implants lowered infection rates to 2.5% , based on meta-analysis syntheses, thanks to better fit and biocompatible materials (24). A meta-analysis of cranio-maxillofacial surgeries found 25% fewer revisions and 18% better functional outcomes with 3D-assisted procedures (1,17). In palliative care, 3D-printed orthoses reduced pressure ulcers by 35% in non-ambulatory patients, per a 2025 scoping review synthesis (4). Adverse events were rare (1–3%), mainly tied to material fatigue but mitigated by ISO-compliant printing (24). Variability in follow-up periods (3–24 months) highlighted the need for standardized outcome measures (6).

Education and Skill Development

In medical education, 3D printing boosted learning and skill development. A meta-analysis of 21 randomized trials showed 25% better performance in anatomical assessments compared to 2D imaging. Undergraduate learners gained 30% more confidence in procedures after training with 3D models, especially in simulation-based curricula for complex surgeries (3). Scoping reviews noted that haptic feedback from 3D models cut error rates by 22% in resident simulations, such as laparoscopic tasks (6). Long-term skill retention (6–12 months) was strong, with 85% of trainees maintaining proficiency gains (8). However, access disparities were evident, with low-resource institutions trailing by 40% in adoption (6). Overall, 3D printing supported interdisciplinary training, aligning with competency-based education goals (3).

Table 2. Outlines key operative outcomes from meta-analyses, highlighting effect sizes and safety metrics.

Study (Year) [Citation ID]	Field (n Studies/Patients)	Primary Outcome	Effect Size (95% CI)	Effect Size Type	Safety Metric	Citation
2025 [24]	Orthopedics (8 studies/450 pts)	Regulatory delays, responsibility gaps, and ethical concerns	-28% (-35 to -21%)	A qualitative synthesis was performed	Infection rate: 2.5% ↓	(24)
2025 [12]	Orthoses (8 studies/320 pts)	Blood loss decrease	-150 mL (-200 to -100)	Mean difference (MD)	Ulcer incidence: 35% ↓	(12)
2023 [28]	Dental (meta, 15 studies)	Flexural strength	SMD -0.45 (-0.72 to -0.18)	Standardized mean difference (SMD)	Fracture risk: Low	(28)
2025 [17]	Prosthetics (10 studies/500 pts)	Functional score (DASH)	+18% (12 to 24%)	Percentage improvement	Satisfaction: 92%	(17)
2025 [3]	Cardiovascular (7 studies/300 pts)	Precision gain	+22% (15 to 29%)	Percentage gain	Blood loss: -120 mL	(3)
2025 [1]	Craniofacial (9 studies/400 pts)	Revision reduction	-18% (-25 to -11%)	Percentage reduction	ISO compliance: High	(1)

Operational Optimization and Managerial Impacts

Thematic synthesis of the 28 studies underscored 3D printing's role in operational streamlining, with 18 reviews quantifying efficiency gains (e.g., 15–35% workflow reductions) and managerial shifts toward decentralized models (6). Cost-benefit analyses highlighted ROI within 6–18 months, while supply chain integrations addressed pandemic-induced disruptions (20). Managerial impacts included enhanced decision-making via data-driven prototyping, though scalability varied by institution size (6).

Cost Analysis and Resource Allocation

3D printing cut costs in device production and resource use, with systematic reviews estimated 20–40% savings per unit through reduced inventory and on-demand manufacturing (20). In prosthetics, localized supply chains saved $500–$1,200 per case by minimizing shipping (28). Radiology services reported $2,900 in time savings per procedure and $2,737 per model, including labor and materials (18). Material efficiency (10–25% less waste) and reduced capital spending allowed reallocation to high-value care (6). A 2025 review noted that 4D/5D printing variants further reduced costs by 15% through adaptive designs (20). Break-even analyses showed viability for production volumes above 50 units per year, with faster prototyping boosting returns (6). Challenges included high upfront costs for printers, though grants offset these in many cases (6).

Table 3. Summarizes cost metrics from key reviews, including savings and allocation impacts.

Context (n Studies/Cases)	Cost Metric	Savings Estimate (95% CI)	Resource Impact	Analysis Level	Citation
Supply chains	Per-unit expense	20-40% ↓ (15-45%)	Inventory reduction: 30%	Systematic review synthesis	(20)
Prostheses (model-based)	Shipping/materials	$500-1,200/case ↓	Waste: 25% ↓	Cost-benefit analysis from scoping review	(17)
Radiology (service analysis)	Total per model	$2,737 (operational)	Time: $2,900/procedure	Systematic review synthesis	(18)
Biomedical (3D/4D/5D)	Adaptive designs	15% ↓ (12-18%)	Personalized allocation	Scoping review synthesis	(20)

Supply Chain and Scalability

3D printing has the potential to transformed supply chains by enabling local production, cutting lead times by 50–70% and addressing shortages (20). Reviews highlighted benefits like 30–50% inventory reductions but noted scalability challenges, including regulatory delays and material standardization issues (24). Extrusion-based methods scaled to high daily outputs in mid-sized labs, but high-volume production faced defect risks without automation (6). Hybrid models combining 3D printing with traditional supply chains improved resilience, though training needs remained substantial (17). Future-focused reviews suggested AI-driven scalability could yield significant efficiency gains (20). Equity gaps persisted, with low-resource settings lagging due to infrastructure limitations (20).

Challenges, Limitations, and Future Directions

The 28 studies revealed ongoing challenges in integrating 3D printing into healthcare management, spanning technical, regulatory, and systemic issues. Regulatory delays, cited in 65% of reviews, slowed clinical adoption by 6–18 months, especially for patient-specific devices requiring Class III certification (7). Material challenges, like inconsistent biocompatibility and mechanical fatigue (10–20% failure rates in long-term implants), were noted in 12 studies, worsened by variability in low-cost printer filaments (24). Scalability was limited by production bottlenecks (e.g., 2–4 hours per complex model), with only 30% of hospitals in resource-constrained settings reporting adequate infrastructure (11). Environmental risks, such as volatile organic compound emissions during printing, raised concerns, with 15–25% higher exposure in poorly ventilated labs (16).

Study limitations included methodological variability (I^2=70–90% in meta-analyses), potential bias toward positive outcomes (funnel plot asymmetry in 40% of syntheses), and underrepresentation of low- and middle-income countries (only 8% of studies) (8). AMSTAR 2 assessments rated 10 studies as critically low, often due to incomplete conflict-of-interest disclosures in industry-funded trials (11). This review's limitations include its reliance on narrative synthesis without quantitative pooling, use of secondary data, and exclusion of pre-2017 studies, which may miss earlier challenges.

Looking ahead, hybrid innovations like AI-driven design optimization could reduce segmentation errors by 40% and improve material durability. Sustainable advancements, such as bio-based filaments and closed-loop recycling, may create 50% greener workflows by 2030 (16). Longitudinal multicenter trials and global equity frameworks are needed to address disparities, while streamlined regulations could speed adoption. Collaboration between engineers, clinicians, and ethicists will be key to unlocking 3D printing's potential for resilient healthcare systems.

From a managerial perspective, hospitals may integrate 3D printing through centralized innovation laboratories, outsourcing partnerships, or department-based rapid prototyping units. Potential implementation areas include surgical planning services, custom prosthetics production, inventory reduction strategies, and emergency supply continuity. Administrators should evaluate return on investment, regulatory compliance, staff training needs, and interoperability with imaging systems before adoption.

CONCLUSION

This systematic review highlights 3D printing as a transformative force in healthcare management, blending clinical precision with operational efficiency to reshape patient care. By enabling tailored solutions that bypass the limitations of traditional methods, it shortens the path from diagnosis to treatment while helping institutions navigate financial pressures. The real challenge lies not just in the technology itself but in ensuring its benefits reach all corners of the global health landscape. Policymakers and administrators must prioritize training, ethical standards, and equitable access to turn challenges into opportunities for progress. Ultimately, 3D printing offers a vision of medicine as unique as the patients it serves, fostering innovation, resilience, and humanity in equal measure.

KAYNAKLAR

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