AUGMENTED REALITY-ENABLED VISUALISATION AND PROCESS CONTROL IN 3D PRINTING AND ADDITIVE MANUFACTURING

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ABSTRACT

Augmented reality (AR) is rapidly emerging as a crucial real-time interface for data visualisation and decision-making in additive manufacturing (AM). This systematic review screened 71 Web of Science records, analysing 15 empirical studies (2021–2025) on AR-enhanced 3D-printing workflows. Reported prototypes, most frequently based on Microsoft HoloLens and MQTT-enabled data streams, demonstrate significant operational improvements such as shorter design cycles, reduced printer downtime and decreased energy consumption per part. Additionally, early fault detection via YOLOv7 overlays and holographic analytics improved print quality and training retention, though studies predominantly used small laboratory samples. Persistent challenges include limited fields of view, latency up to 8 seconds, and proprietary firmware hindering bi-directional data exchange. Interpreting these findings using an extended Technology Acceptance Model indicates that open printer architectures and AI-driven context-sensitive guidance systems are essential for advancing AR-AM from isolated demonstrations to scalable industrial practice.

KEYWORDS

Augmented Reality, 3D Printing, Additive Manufacturing, Human-machine Interaction, Industry 4.0, Industry 5.0, Digital Twin

1 INTRODUCTION

Mass customisation and the "right-first-time" requirement are among the most frequently cited objectives of Industry 4.0/5.0. A systematic review of augmented reality (AR) integration into industrial manufacturing demonstrates that reducing error rates and setup times are among its most consistently evidenced benefits (Morales Méndez 2024). At the same time, a review of developments in additive manufacturing (AM) techniques documents the increasing demand for flexible production and bespoke complex geometries (Ramos 2025).

1.1 *Augmented Reality: Definition and Technological Foundations*

Azuma defined augmented reality as a technology that (i) combines real and virtual objects, (ii) operates interactively in real time, and (iii) is spatially, three-dimensionally registered. This triad continues to serve as a foundational guideline for contemporary research (Azuma 1997). Milgram and Kishino expanded this perspective through the Reality–Virtuality continuum, which positions augmented reality and mixed reality (MR) between entirely real and entirely virtual environments, thereby facilitating the classification of hybrid systems (Milgram 1994). More recent reviews emphasise that contemporary definitions are frequently expanded to include multimodal interactions (voice, gestures, haptics) and integration with digital twins in the context of Industry 4.0 (Morales Méndez 2024). Extended reality (XR) is an umbrella term for technologies that blend or augment perceptions of real and computer-generated environments, specifically encompassing augmented reality, virtual reality, and mixed reality. In the scientific literature, XR is described as a continuum, where AR is positioned closer to the physical world, VR provides full immersion in a simulated environment, and MR enables bidirectional interactions between virtual and real objects (Rauschnabel 2022) (Shatokhin 2025).

Optical see-through near-eye displays (OST NEDs), transparent lenses with embedded virtual imagery, are experiencing rapid miniaturisation. Current prototypes typically employ micro-LED or micro-OLED panels. This reduction in size results in decreased weight and lower power consumption, both of which are essential for operators engaged in all-day tasks (Xia 2022) (Sun 2025). Field of view (FOV) remains the most significant barrier: typical headsets currently provide 35-55°, whereas human peripheral vision is approximately 120° (Eisenberg 2020).

1.2 *Industrial Augmented Reality Applications*

A review of XR in design and manufacturing identifies projection-based systems as promising for collaborative assembly tasks, although challenging in terms of calibration requirements (Chu 2024). Recent empirical studies consistently demonstrate that AR enhances the efficiency of critical industrial tasks. In assembly operations, instructions projected onto head-mounted displays (HMDs) reduced error rates by 25-40% and shortened operation times by nearly one-third (O'Keeffe 2024) (Mao 2025). In maintenance and servicing, hands-free guidance led to an average reduction in repair times of 30% and facilitated quicker recommissioning of machinery (Alessa 2023) (Malta 2023). Furthermore, AR-supported training and safety instruction significantly improved knowledge retention and procedural compliance compared with traditional methods (Gong 2024) (Yang 2023). Comprehensive analyses also indicate that subjective cognitive load, measured via NASA-TLX, decreases even when tasks are completed more rapidly. However, the limited field of view and battery life of current HMDs remain open challenges 2024) (Hou 2025).

1.3 *Additive Manufacturing: Process Fundamentals and Trends*

Additive manufacturing is a production process in which materials (e.g., polymers, metals, or composites) are successively layered to create a final product. This fundamentally distinguishes it from conventional subtractive manufacturing, which instead removes material from an initial block or workpiece (DeBoer 2021) (Pagac 2021) (Sun 2023). An analysis of articles indicates an almost exponential increase in scientific activity and an expansion of research topics towards design-for-AM and machine learning applications (Obi 2022) (Ma 2024). A collection of studies on "AM and supply-chain resilience" demonstrates that distributed manufacturing shortens supply chains and enhances resilience to disruptions (Keskin 2025) (Bouchenine 2023). However, reviews of in-situ monitoring methods emphasise that achieving "right-first time" quality remains dependent on rapid process sensing. Notably, a novel training-free optical inspection technique has successfully detected deviations in laser powder bed fusion (PBF) without requiring prior model training (Tosoratti 2025) (AbouelNour 2022). Sustainability is another accelerating theme. Life cycle assessments indicate that material-efficient geometries and localised production can offset the high energy demands of certain printing processes, provided that closed loop recycling of powders and polymers is achieved. This remains a key challenge in current "green 3D printing" research (Pongwisuthiruchte 2025).

1.4 *The Rationale behind Integrating Augmented Reality into Additive Manufacturing*

Experiments with AR-based training for laser PBF operators have shown improved defect diagnosis accuracy and reduced onboarding times through the integration of object and text recognition capabilities in head-mounted displays (HMDs) (Zhang 2024) (Fan 2024). A review of digital twins for Wire-Arc AM emphasises that visual overlays of process parameters facilitate predictive control of the melt pool and generally improve deposition stability (Li 2024). A systematic review of HMD-AR applications in manufacturing summarises that such interfaces reduce interruptions for consulting external screens, but also highlights persistent limitations in terms of field of view, device weight, and latency, which currently hinder widespread adoption (Fang 2023).

These findings indicate that augmented reality can serve as an "instant visual channel" for additive manufacturing process data, a role similarly highlighted in a recent AR and IoT literature review which identifies AR as a comparable rapid access conduit within industrial data flows (Macháč 2025). Nevertheless, it is important to acknowledge the associated risks and challenges of integrating augmented reality into additive manufacturing. Among the principal concerns is insufficient accuracy in the registration of virtual objects with the real environment, which could lead to misinterpretation of critical manufacturing data and consequently introduce errors into the production process (De Pace 2020) (Havlíková 2023). Additionally, prolonged use of AR devices, particularly HMDs, may increase physical fatigue or discomfort for operators (Kosmowski 2024). From an interaction perspective, there is a risk of overwhelming users with excessive information if data are not presented clearly and contextually (Alessa 2023). Lastly, standardisation of data interfaces between AR systems and additive manufacturing equipment remains an unresolved challenge (Liu 2022) (Li 2024) (Fisher 2019).

1.5 *Summary and Research Questions*

The fields of augmented reality and additive manufacturing currently represent rapidly evolving research areas and constitute key technologies for the future of industrial production. Nevertheless, a systematic overview summarising recent trends and advancements in the integration of AR with industrial 3D printing remains absent from contemporary scholarly literature. Existing research contributions have predominantly addressed isolated applications of AR in specific phases of the 3D printing lifecycle, such as preparation and setup prior to manufacturing, in-situ monitoring during production, and subsequent quality control post-printing.

For instance, recent studies have documented individual cases including the use of AR for repairing desktop fused deposition modelling (FDM) printers (Tadeja 2023), utilisation of projectors for visual inspection of printed prototypes (Omaia 2024), and the integration of digital twins in the Wire-Arc additive manufacturing process (Mahdi 2025). Parallel bibliometric analyses within the AM field alone confirm a significant increase in scientific activity (31% annually up to 2024) yet simultaneously highlight insufficient representation of topics such as AR technology integration, data-driven feedback, and operator ergonomics (Dehghan 2025).

The following research questions are proposed to guide this study:

RQ1: How is augmented reality technology currently applied within additive 3D printing processes?

RQ2: What dominant augmented reality approaches, benefits and challenges accompany its integration into industrial additive manufacturing?

Augmented reality is rapidly penetrating the field of additive manufacturing, yet existing research remains fragmented and lacks a unified framework. Our aim is to address this gap by providing a comprehensive study that:

- **Standardises terminology and use-case scenarios** through a four-pillar taxonomy, ranging from printer monitoring to interactive training aligned with the "right-to-repair" philosophy.
- **Highlights the primary advantages and limitations of current AR solutions**, enabling readers to swiftly discern areas where AR genuinely adds value and those where it encounters constraints.
- **Identifies key methodological and technical barriers**—including research designs, hardware limitations, and proprietary interfaces—and critically calls for their resolution.
- **Presents eight specific design recommendations** to guide future research and industrial implementation of AR–AM systems.

The structure of the paper is as follows:

Methodology – detailing a systematic literature search conducted in the Web of Science Core Collection (WoS) citation database, along with analytical procedures ensuring transparency and reproducibility.

Results – introducing the proposed taxonomy, synthesising identified benefits, and outlining recognised limitations.

Discussion – linking findings with existing theoretical frameworks, analysing practical implications, and critically examining current barriers.

Conclusion – summarising key insights and proposing actionable guidelines aimed at inspiring future research and industrial initiatives.

2 LITERATURE REVIEW METHODOLOGY

In this section, we present a concise literature review, compiled through a structured systematic survey, which critically evaluates contemporary augmented reality (AR) technology within the broader context of 3D printing and additive manufacturing. The methodological framework underpinning our systematic review adheres to well-established principles, involving clear identification of the research problem followed by a comprehensive analysis of relevant literature (Garousi 2019). Importantly, this overview is deliberately succinct, providing a focused examination of the selected topic.

Our methodology includes an extensive examination of peer-reviewed scholarly articles and academic publications. The selection and filtration of literature are guided by explicitly defined research objectives, ensuring that only pertinent studies are included. This targeted selection facilitates the derivation of insightful conclusions and meaningful results (Higgins 2019). Consequently, this methodological approach ensures a rigorous evaluation of the existing knowledge base, contributing to a thorough understanding of the applications and implications of augmented reality integrated with 3D printing and additive manufacturing technologies.

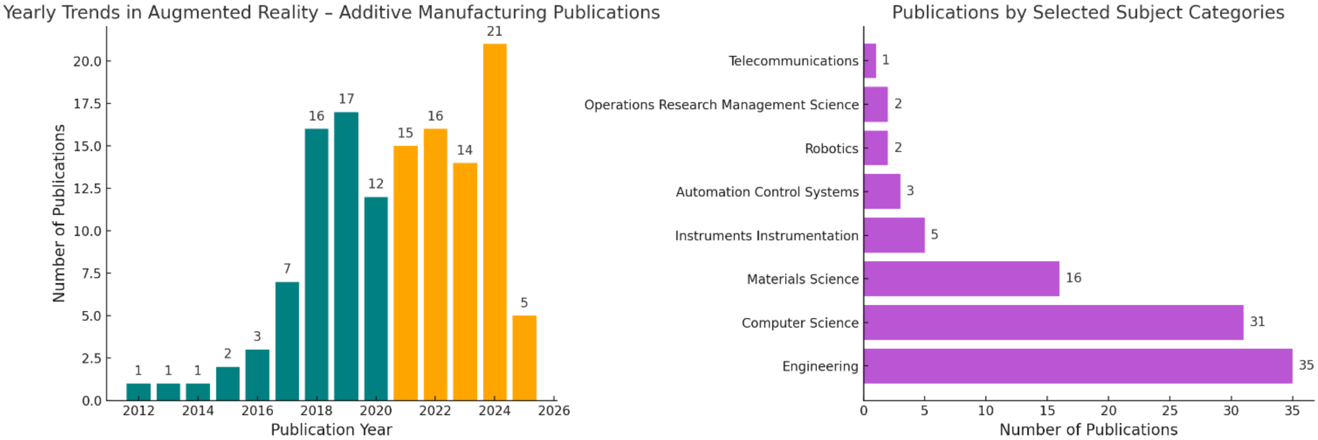

Figure 1. Publications in augmented reality and additive manufacturing. Left: Yearly trends of publications. Right: Distribution by selected subject categories.

2.1 *Research Procedure Selection*

In this research, we employed a methodology that comprehensively delineates the necessary steps for conducting systematic literature searches and the subsequent analysis of retrieved data. Our systematic review concentrates specifically on a targeted scope, in contrast to traditional approaches that generally involve a broader evaluation of the available literature. Given the relative novelty of the subject matter, the initial phase involved an in-depth exploration of this research area. We utilised a methodological framework defining systematic literature review as a structured examination of a range of peer-reviewed publications over several years, enabling the extraction of rich analytical data (Okoli 2010).

The application of a methodically filtered procedure enabled us to gather relevant information in a clearly defined manner, thereby minimising systematic errors. This approach comprises the identification, evaluation, and synthesis of all pertinent studies aligned with the selected methodology. The initial implementation of our research involved selecting primary sources based on predefined keywords. Following the removal of irrelevant and duplicate sources, we performed qualitative assessments focusing on the review of titles, abstracts, and publication scopes. The final phase involved synthesising the findings in relation to the original research questions.

For the literature search, we employed a mixed-methods research approach that integrates both quantitative and qualitative methodologies. The initial stage involved systematic searching of selected citation databases, specifically the **Web of Science Core Collection (WoS)**, to compile the source corpus. This dataset was subsequently subjected to both quantitative (e.g., bibliometric counts, trend analysis) and qualitative (e.g., relevance screening, thematic synthesis) analyses.

2.2 *Search Query Formulation*

The query was implemented by applying a filter directly within the WoS interface on 16 July 2025. This approach allowed for the quantitative identification of relevant publications directly corresponding to the search query. To further refine the results, basic selection criteria were applied.

The specification of the paper's topic was determined based on the occurrence of selected keywords identified through the search query, specifically focusing on publication titles and keywords, according to the following query:

TI=(

("augmented reality" OR "mixed reality" OR "extended reality" OR "AR" OR "XR" OR "MR" OR "smart glasses" OR "head-mounted display" OR "wearable technology" OR "augmented visualisation" OR "augmented manufacturing" OR "immersive technology" OR "augmented assistance" OR "AR-based" OR "mixed-reality interface" OR "industrial AR")

AND

("3D printing" OR "additive manufacturing" OR "3D printing monitoring" OR "in-situ monitoring" OR "print process visualisation" OR "AR-assisted printing" OR "3D fabrication" OR "3D printer" OR "3D printed object" OR "printed part")

)

OR

AK=(

("augmented reality" OR "mixed reality" OR "extended reality" OR "AR" OR "XR" OR "MR" OR "smart glasses" OR "head-mounted display" OR "wearable technology" OR "augmented visualisation" OR "augmented manufacturing" OR "immersive technology" OR "augmented assistance" OR "AR-based" OR "mixed-reality interface" OR "industrial AR")

AND

("3D printing" OR "additive manufacturing" OR "3D printing monitoring" OR "in-situ monitoring" OR "print process visualisation" OR "AR-assisted printing" OR "3D fabrication" OR "3D printer" OR "3D printed object" OR "printed part"))

AND

Article or Proceeding Paper (Document Types)

AND

2021 or 2022 or 2023 or 2024 or 2025 (Publication Years)

AND

Engineering or Computer Science or Materials Science or Instruments Instrumentation or Automation Control Systems or Robotics or Operations Research Management Science or Telecommunications (Research Areas)

To analyse current trends at the intersection of augmented reality and additive manufacturing, a filter was developed in the Web of Science (WoS) database. This filter combines two extensive sets of keywords: one encompassing terminology related to AR/MR/XR (e.g., "augmented reality", "smart glasses", "immersive technology") and the other addressing additive manufacturing terms (e.g., "additive manufacturing", "in-situ monitoring", "3D printed object"). The logical operator "AND" was utilised between these two keyword groups to ensure the identification of publications explicitly addressing the integration of both fields, thus excluding general studies that focus solely on either AR or 3D printing independently.

The keyword search targeted the title (TI) and author keywords (AK) fields to capture articles where authors have explicitly emphasised the relationship between these two technologies, thereby minimising irrelevant results caused by peripheral mentions within abstracts or main texts. Document types were restricted to "Article" and "Proceeding Paper" to ensure peer-reviewed quality and to include the most recent findings presented at scientific conferences. The chosen time frame (2021–2025) reflects the rapid advancement observed in both technologies in the post-pandemic period. Additionally, selecting specific research areas (e.g., Engineering, Computer Science, Materials Science) further refined the search, focusing exclusively on technically relevant publications and excluding purely social science studies, which would be peripheral to the aims of this review. Overall, this approach generated a targeted yet sufficiently comprehensive dataset that captures both fundamental research and practical engineering implementations of augmented reality in additive manufacturing over the past five years.

2.3 *Research Results*

A quantitative analysis of scientific publications retrieved from the selected database, using the defined search query, identified 71 relevant publications published within the past five years. In the subsequent phase of this iterative process, these initial results underwent a rigorous qualitative evaluation to determine their relevance.

The bar chart (**Fig. 1**) illustrates the progression of filtered publication activity from 2012 to 2025. Following sporadic occurrences between 2012 and 2016 (≤ 3 articles per year), a significant increase emerged, rising sharply from 7 publications in 2017 to 16 and 17 publications in 2018 and 2019, respectively. A brief decline observed in 2020 (12 publications) correlates with pandemic-related constraints. However, publication numbers subsequently recovered, consistently reaching 15-16 per year, with a peak of 21 in 2024. Data for 2025 (currently 5 publications) remain incomplete. The examined period is highlighted by the orange bars (2021–2025), confirming that the most intensive research activity has indeed occurred during these recent years. Moreover, the distribution of publications across subject categories (**Fig. 1**) indicates that the largest proportions of relevant studies are found within Engineering (35 publications) and Computer Science (31 publications), highlighting the predominance of technically and computationally oriented research.

This step involved verifying the origin and credibility of each publication. Furthermore, the content of each publication was manually reviewed, with particular attention given to the specific focus articulated within the title and abstract, in relation to the research objective. Following this detailed assessment, only 15 publications were identified as fulfilling the relevance criteria required for inclusion in the next phase of the research. Specifically, publications had to satisfy the following conditions:

- **Technological Integration:** Studies should demonstrate the involvement of augmented or mixed reality within at least one key phase of additive manufacturing (e.g., pre-print configuration, in-situ monitoring, adaptive process parameter control, or operator assistance). Merely providing ex-post visualisation of a finished print or adding informational overlays to completed products is insufficient.
- **Experimental or Applied Nature:** Only studies featuring validated prototypes, laboratory experiments, or industrial demonstrations were included. Purely conceptual proposals, proof-of-concept studies without practical implementation, and review articles were excluded, as they do not provide empirical evidence demonstrating the integration of both technologies.
- **Relevance to Non-Medical Technical Applications:** Most medical studies utilise 3D printing solely as a carrier (e.g., implants, anatomical models) and augmented reality primarily as a navigational interface. Such studies were excluded unless they explicitly involved direct control or optimisation of the printing process.
- **Novelty and Innovativeness:** Studies should present novel methods, algorithms, or hardware developed between 2021 and 2025. Research replicating earlier approaches was excluded.

In the preliminary corpus of 71 records, the majority comprised articles in which augmented reality and 3D printing were discussed in parallel, rather than synergistically. By introducing the criterion of technological integration, we excluded publications in which augmented reality served merely as a visualisation tool for the final product.

Using VOSviewer (full counting method, association strength normalisation, minimum co-occurrence = 4), we generated a network visualisation (**Fig. 2**) illustrating the co-occurrence of key terms within the filtered publications. From the 1.512 terms initially identified, 78 met the threshold criteria, with the top 60% in terms of relevance equating to 47 terms retained for analysis. Clusters were identified using the VOSviewer modularity optimisation (VOS) clustering algorithm, which subsequently assigned colours as described below.

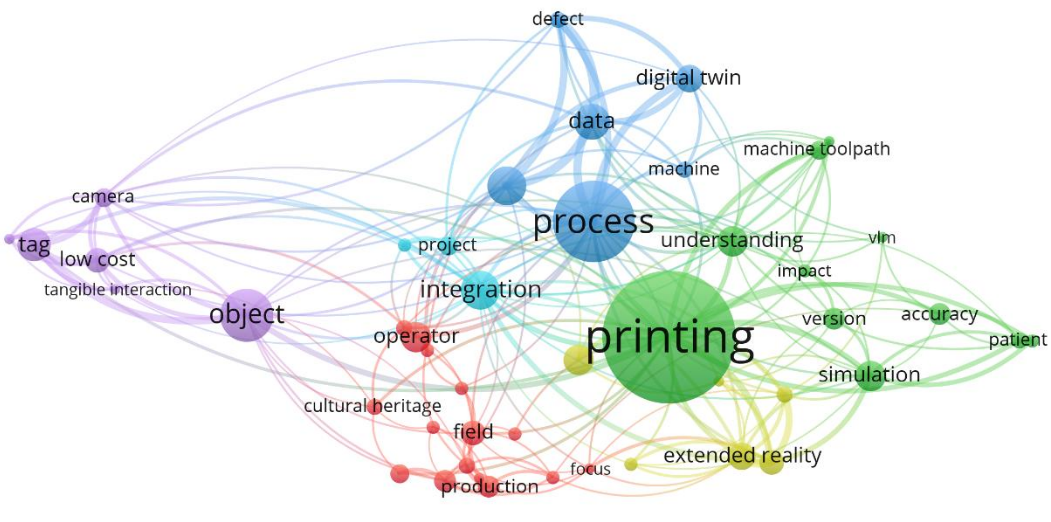

Figure 2. Keyword distribution and interactions using VOSviewer

Authors	Number of Citations	Title of Publication	Year
Bakkiyaraj et al.	6	Impact of Augmented Reality on Learning Fused Deposition Modeling-based 3D Printing – Augmented Reality for Skill Development (Bakkiyaraj 2021)	2021
Bozzi et al.	8	Towards Augmented Reality Guiding Systems: An Engineering Design of an Immersive System for Complex 3D Printing Repair Process (Bozzi 2023)	2023
Comes et al.	0	Augmented Reality Guided 3D Printed Robotic Arm Assembly: A Comprehensive Framework for Interactive Learning (Comes 2024)	2024
Covarrubias et al.	0	Extended Reality for Special Educational Needs: From the Design Process to Real Products Through 3D Printing (Covarrubias 2024)	2024
Dogan et al.	27	InfraredTags: Embedding Invisible AR Markers and Barcodes Using Low-Cost, Infrared-Based 3D Printing and Imaging Tools (Dogan 2022)	2022
Fan et al.	5	Enhancing Metal Additive Manufacturing Training with the Advanced Vision Language Model: A Pathway to Immersive Augmented Reality Training for Non-Experts (Fan 2024)	2024
Kaščák et al.	0	Advanced Approaches to Material Processing in FFF 3D Printing: Integration of AR-Guided Maintenance for Optimized Manufacturing (Kaščak 2025)	2025
Lipkowitz and DeSimone	0	Palette-PrintAR: Augmented Reality Design and Simulation for Multicolor Resin 3D Printing (Lipkowitz 2024)	2024
McKelvey et al.	0	A Human-Centered Intelligent Platform for Holographic Control and Management of 3D Printers (McKelvey 2024)	2024
Passananti et al.	0	Augmented Reality for Digital Fabrication: Evaluating Impact of AR Visualization of Machine Toolpaths for Clay 3D Printing (Passananti 2024)	2024
Passananti et al.	0	SculptAR: Direct Manipulations of Machine Toolpaths in Augmented Reality for 3D Clay Printing (Passananti 2023)	2023
Tadeja et al.	8	Exploring the Repair Process of a 3D Printer Using Augmented-Reality-Based Guidance (Tadeja 2023)	2023
Yi et al.	29	Process Monitoring of Economic and Environmental Performance of a Material Extrusion Printer Using an Augmented-Reality-Based Digital Twin (Yi 2021)	2021
Zhang et al.	1	Object Detection and Text Recognition for Immersive Augmented Reality Training in Laser Powder Bed Fusion (Zhang 2024)	2024
Zimmermann et al.	2	Visualizing Defects of Concrete 3D Printed Structures with Augmented Reality Based on Machine Learning-Driven Image Analysis (Zimmermann 2024)	2024

Table 1. Shortlisted publications and their authors by number of citations

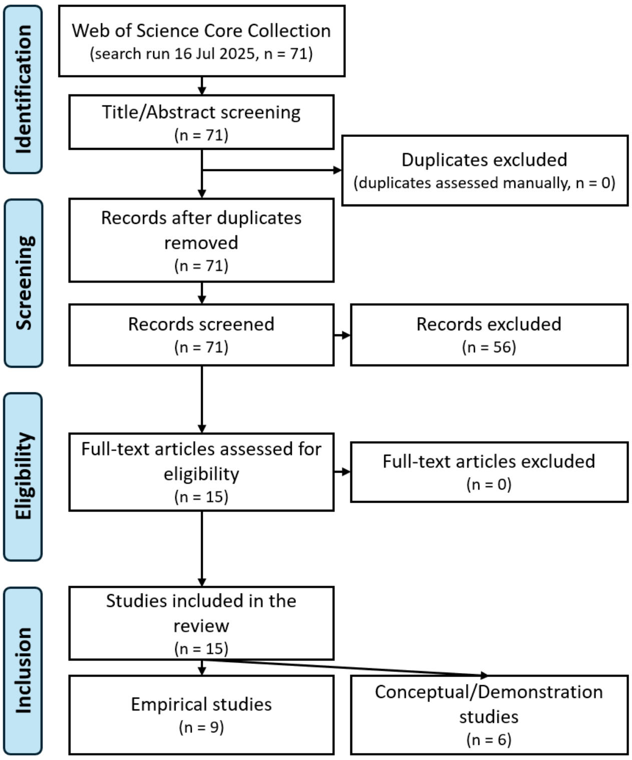

Figure 3. PRISMA flow diagram

The dominant node, 'printing' (green), bridges the blue cluster oriented around 'process', 'data', and 'digital twin' and the green cluster associated with 'simulation' and 'extended reality'. The purple cluster positioned on the left ('object', 'camera', 'low-cost') represents research focusing on postprocessing visualisation, whereas the smaller red cluster ('field', 'production', 'operator') denotes operational deployment. The relatively weak connections observed between 'extended reality' and 'process' indicate that direct integration of augmented reality within additive manufacturing control remains infrequent. Research to date has primarily utilised augmented reality for monitoring and simulation purposes. Fully integrated augmented reality additive manufacturing (AR-AM) solutions continue to be rare, highlighting a clear need for further research and development in this domain.

The stages of record identification, screening, eligibility, and inclusion are illustrated by the PRISMA flow diagram (**Fig. 3**), populated with data from a Web of Science search conducted on 16 July 2025 (71 records reduced to 15 included studies) and following an extended PRISMA flow format (Vu-Ngoc 2018).

3 RESULTS

Analysis of the trend curve for publications filtered as of 16 July 2025 (**Tab. 1**) reveals a significant increase between 2021 and 2024. Out of the total 15 records, more than half (53%) correspond to the year 2024, whereas only two articles were identified in 2021. After a temporary decline to one publication in 2022, the number rose to three in 2023 and reached a peak of eight publications in 2024. This represents a fourfold increase compared to the year 2021. Preliminary data for the ongoing year 2025, with just one article so far, do not yet permit conclusions about whether this upward trend will continue.

The distribution of filtered studies indicates a strong predominance of prototype-oriented research. The category of prototype design and presentation comprises 10 out of 15 articles (approximately 67%), with seven classified as design papers and three as standalone studies describing the construction or demonstration of prototypes. Pure user studies, which include laboratory, quasi-experimental or field evaluations, account for four publications (approximately 27%).

A separate but marginal category consists of a single engineering design study combined with qualitative expert inquiry (approximately 7%). This distribution reveals that the research field under investigation primarily emphasises the development and demonstration of technical solutions, whereas systematic user-centred evaluation remains comparatively less represented.

Analysis revealed five dominant areas, each directly influencing the design, implementation and evaluation of XR systems supporting additive manufacturing. The following summary concisely outlines the key features of these areas.

- **System architecture:** Most prototypes adopt a three-layer model comprising printing hardware and firmware connected via a server layer (MQTT, WebSocket) to a client developed in Unity and MRTK for HoloLens headsets. This configuration unifies remote control and device monitoring within an MR environment.
- **Computer vision and digital twins:** Approximately one-third of studies integrate CNN or YOLOv7 (mAP ≈ 0.85) along with CRAFT OCR to detect defects and recognise text. Findings are projected onto a digital twin (SolidWorks) for real-time visualisation of defects.
- **CAD workflow and generative tools:** Prototypes typically use exports of STEP/OBJ files or G-code from parametric CAD software. Recent studies also explore LLMs (Vicuna-based) for automated data synthesis and validation or connect Rhino and Grasshopper with Fologram for data streaming.
- **Experimental design and metrics:** Evaluations are generally small scale (3 to 40 participants) and commonly utilise think-aloud protocols, NASA-TLX and the Short Flow Scale, alongside analyses such as RM-ANOVA or Kirkpatrick models (levels 1 and 2) to measure performance and cognitive load.
- **Task scenarios and multimodal instructions:** Tasks involve between 5 and 22 assembly steps validated through FAST analysis. Instructions are delivered via text, audio, video or 3D CAD. According to existing measurements, these multimodal approaches reduce task completion time and improve immediate retention, although longitudinal data remain lacking.

Of the total 15 articles included in the review, nine were empirical studies, while the remaining six were conceptual or demonstrative in nature, involving prototypes or laboratory measurements without user samples. The nine empirical studies involved a total of 88 participants, of whom approximately 78% (n = 69) were non-experts (students, volunteers, or individuals with special educational needs) and 22% (n = 19) were professionals - 3D printing operators, PhD-qualified engineers, or creative artisans. Participants' ages ranged from 19 to 35 years (median ≈ 25 years). Sample sizes varied significantly, from a single operator managing simulated printer malfunctions to a quasi-experiment involving 40 students without previous 3D printing experience. The remaining studies examined smaller, specialised cohorts: two groups of three PhD-qualified engineers, ten students with special educational needs, two volunteer mechanics without prior experience, nine creative professionals, and a pilot cohort consisting of seventeen non-experts.

Across the analysed experiments, augmented reality featuring a digital twin supported by YOLOv7-based defect detection (mAP ≈ 0.85) and holographic charts enabled early fault identification and preventive suspension of printing, reducing both defective outputs and unplanned downtime by more than a third. Overlaying CAD (computer-aided design) and CFD (computational fluid dynamics) data directly at the point of operation, together with multimodal instructions, shortened start-up and assembly times by 34% and 40%, respectively, reduced the need for expert intervention by 86%, and improved task retention from 59% to 78%. Student and volunteer groups reported high usability scores and perceived the system as highly beneficial, demonstrating enhanced motor and cognitive performance as well as increased confidence during practical tasks. Both experienced operators and novices valued measurement accuracy, with eight out of nine designs falling within the reference range, and appreciated improved fault diagnostics. Nevertheless, they highlighted the narrow field of view, increased headset weight, and unreliable gesture recognition when wearing gloves as limitations. For future implementations, it is recommended to validate the system under real operational conditions, introduce clear safety warnings requiring mandatory confirmation of procedural steps, allow user-customisable configurations and spatial anchoring of instructional elements, provide initial user training, and ensure software optimisation for smooth system operation.

The reviewed set of studies predominantly employs Microsoft HoloLens 2 or the original HoloLens 1 headsets in combination with various classes of 3D printers, ranging from desktop models such as Creality Ender 3, Prusa i3 MK3S, CR 20 Pro and Sharebot to industrial-grade systems including Renishaw RenAM 500M, AM400 and Carbon3D M1. Visual instructions are supported by tablets and smartphones equipped with LiDAR or cameras, whereas control and monitoring functions rely on Raspberry Pi minicomputers, standard PCs or, in one case, a server equipped with four NVIDIA A100 graphics processing units. Positional accuracy is enhanced through QR codes, white background scenes and cameras attached to printer heads. Several scenarios additionally incorporate heat-resistant gloves, manual tools and backup power supplies, illustrating an effort to validate prototypes under realistic operating conditions.

Based on a critical analysis of current studies integrating augmented reality with additive manufacturing, four key pillars of application can be identified: (i) monitoring and predictive maintenance of 3D printers, (ii) in-situ component design and validation, (iii) enhanced inspection and logistical tracking of objects and (iv) interactive training including right to repair initiatives.

4 DISCUSSION

AR applications presented in the conclusions reflect a shift from isolated demonstration projects towards integrated socio-technical ecosystems within industry. This study provides a framework for further theoretical and practical exploration regarding the role of AR in additive manufacturing. From a theoretical perspective, our findings support an extended Technology Acceptance Model (TAM), indicating that the benefits of AR extend beyond perceived usefulness (e.g., improved productivity and reduced waste) to include perceived enjoyment and immersion (Wang 2024). Additionally, the relevance of situated learning concepts is confirmed, as operators develop maintenance and design skills directly within the context of specific machinery and tasks, thereby bridging the gap between training and actual practice. The greatest benefits of AR emerge from authentic or situated learning scenarios, where AR seamlessly integrates physical and virtual environments, facilitating learning directly within real-world contexts. Concurrently, the inspection and logistics pillar extends the lean maintenance paradigm by employing digital twins and augmented reality to facilitate immediate visualisation of quality-related data and potential defects, thereby enabling quality inspections to occur simultaneously with production. For instance, augmented reality can project instructions and diagnostic data onto equipment in real time, accelerating decision-making processes and enabling rapid detection of problems during production.

In human resources and training, XR serves as a catalyst for inclusion, as multimodal AR/VR guides accommodate diverse learning styles, making procedures more accessible to users with disabilities or special educational needs. Voice-based, visual, and haptic instructions in AR facilitate training even for individuals challenged by traditional instructional methods. Additionally, XR technologies support the "right-to-repair" initiative, with interactive AR instructions significantly enhancing training effectiveness for operators and end-users, consequently extending equipment lifespan and reducing electronic waste.

However, current findings on AR applications in additive manufacturing exhibit significant methodological and technical limitations, substantially restricting the generalisability of conclusions. Most studies involve very small and often homogeneous samples (typically 2–17 participants, primarily experts) and lack control groups or quantitative comparisons with alternative platforms, thus leaving long-term skill retention effects largely undocumented. Tested prototypes are highly heterogeneous in hardware, software, and printing technologies, with most experiments conducted in controlled laboratory settings over short durations, and a notable absence of longitudinal data from real-world operations.

Technical constraints significantly impact system functionality, including narrow fields of view and headset weight, manual or QR-based model alignment, camera sensitivity to lighting conditions, and tracking jitter under poor illumination. Applications often exhibit latency of up to eight seconds during local processing or suffer from low frame rates on mobile devices, destabilising visual guidance. Printer integration is frequently unidirectional, with limited support for specific machine types or shapes, and network outages exacerbate the 'reality gap'. Hardware fragmentation, including variations in resolution, dust and vibration resistance, and ergonomics, further complicates standardisation. These issues, together with reported musculoskeletal strain and cybersecurity risks, underscoring the necessity for a comprehensive security framework.

Without more rigorous methodologies (larger, diverse samples, control groups, validated UX metrics, and long-term field studies), robust hardware improvements (broader FOV, resilient tracking, reduced latency), and standardised integration interfaces, scalable and sustainable industrial adoption of AR in 3D printing remains uncertain.

Contemporary 3D printers, ranging from industrial-grade systems to hobbyist models, frequently employ closed architectures that substantially limit opportunities for open research. Manufacturers commonly safeguard proprietary expertise through closed firmware and hardware, preventing engineers and developers from accessing internal printing process data or modifying printers for experimental purposes. Consequently, integrating new technologies (e.g., sensors, augmented reality) or custom software becomes exceedingly challenging. Without open interfaces, obtaining real-time data on temperature, print speed or print progress, which are critical for additive manufacturing research and optimisation, is highly problematic.

Open-source platforms such as OctoPrint offer uncommon opportunities for integrating external applications through the extraction and dissemination of printer data. Nevertheless, not all printers support this type of integration, which frequently requires substantial modifications (Rysbek 2024). Advancing AR research in additive manufacturing thus requires opening printer systems. Without open data interfaces and hardware customisation capabilities, the research potential of these devices remains largely untapped. Open architectures are not merely ideological but are practically essential for enabling community-driven knowledge exchange, technological improvements, and genuine progress in additive technologies.

Another crucial point for discussion is the novelty of combining AR and additive manufacturing and the resulting limited scientific community interest. Publication activity in this domain remains minimal; as recently as 2024, only a small number of studies specifically addressed AR integration with 3D printing. Such a limited number of publications hardly constitutes an established research direction or robust trend. Although both augmented reality and advanced additive manufacturing are relatively novel, and their integration logically remains at an early stage, it remains uncertain whether the scientific community will perceive this topic as sufficiently innovative or appealing to justify significant research investment. Notably, research explicitly exploring AR in additive manufacturing processes remains rare.

From a critical perspective, this constitutes a highly specialised and narrowly scoped application of AR, aimed primarily at optimising a particular industrial process rather than delivering broader transformative impacts. While incremental technological advancements are inherently valuable, the broader question persists as to whether such narrowly defined innovations can attract widespread attention and garner support compared to projects addressing immediate safety or societal challenges. It is imperative to critically assess genuine contributions: for AR to significantly impact additive manufacturing, it must either offer tangible advantages unavailable through current methods or integrate effectively into broader concepts, such as smart manufacturing ecosystems. Without this, it risks remaining limited to experimental settings, resulting in a delayed transition into practical applications due to insufficient urgency.

An additional promising direction involves deeper integration of AR with artificial intelligence (AI) and generative design. Advanced AI tools can analyse printer and design-process data in real-time, providing adaptive recommendations to operators. Existing experimental integrations of AR glasses with large language models demonstrate systems capable of recognising text or objects and presenting corresponding AR-based maintenance instructions. Such synergy could further streamline decision-making processes, with AI systems suggesting optimal interventions or design modifications clearly communicated through AR interfaces. Generative design techniques could facilitate interactive AR exploration and development of novel AI-optimised shapes, positioning operators as curators selecting from algorithmically generated variants. This integration of AR and AI promises substantial enhancements in adaptability and intelligence within the manufacturing ecosystem (Devagiri 2022) (Mayer 2025).

5 CONCLUSIONS

This review addressed two research questions. **RQ1:** How is AR currently applied within additive-manufacturing workflows? and **RQ2:** Which dominant approaches, benefits and challenges accompany this integration? By screening 71 WoS-indexed records and qualitatively appraising 15 empirical papers published between 2021-2025, we unified a previously fragmented body of work into four application pillars: predictive monitoring, in-situ design validation, AR-enhanced inspection/logistics and interactive "right-to-repair" training. We further observed notable improvements, such as meaningful decreases in downtime, lower energy use per unit produced, and shorter design-cycle durations. Additionally, we provided the first systematic audit of hardware-related, methodological, and organisational bottlenecks that continue to impede wider industrial adoption.

The findings support an extended Technology Acceptance Model (TAM), indicating that the value of AR arises not only from its perceived usefulness but also from the enjoyment and sense of immersion it affords—factors which enhance learning motivation in real-world, shop floor environments. At the same time, lean-maintenance concepts are broadened through digital twins that project real-time quality data directly onto parts in production. Nevertheless, most prototypes are still confined to the laboratory: limited-FOV headsets, closed printer firmware, manual alignment, and noticeable latency restrict scalability, while participant samples remain small and longitudinal evidence is scarce.

Unlocking the full potential of AR-AM demands (i) open printer architectures that expose high-frequency process data for research and sensor fusion; (ii) rigorous field trials with diverse user cohorts to capture long-term skill retention and productivity effects; and (iii) a deep fusion of AR front-ends with AI-driven analytics and generative design, where multimodal LLMs translate real-time cues into adaptive, step-wise guidance. Such a data-centric ecosystem can elevate AR from a visual add-on to an intelligent decision-making partner in Industry 4.0/5.0.

Based on our analysis, we propose the following actionable guidelines, intended to guide future research and provide practical recommendations for everyday industrial implementation of AR in additive manufacturing:

- **Leverage data at scale** – Continuously log high-resolution process data and apply machine-learning models to predict faults across every HMI (Human-machine Interaction) step; extend the same framework to adjacent CNC (GRBL) workflows.

- **Automate spatial alignment and vision** – Adopt multi-camera setups with automatic ICP alignment and CNNs robust to poor lighting to ensure reliable model-to-scene registration without manual tweaking.

- **Embed live, multimodal sensing** – Stream real-time signals from extruder, temperature, vibration and flow sensors into the XR layer; expose them through open IoT platforms (e.g., ThingsBoard or DeviceHive) for predictive diagnostics.

- **Minimise latency, maximise ergonomics** – Optimise network (WebSocket) and AI inference pipelines to stay below perceptible delay and deploy lighter HMDs with wider FOV; compare HMD and handheld form factors in structured SUS studies.

- **Strengthen tracking resilience** – Develop deep-learning trackers that tolerate gloves, occlusions and variable illumination, and pair them with telepresence expert support and gamified feedback loops.

- **Enable adaptive manufacturing decisions** – Automate support-generation for excessive overhangs, integrate remote task preparation and control, and adopt high-resolution cameras for infrared (IR) or retroreflective tagging on curved surfaces.

- **Validate with rigorous, longitudinal trials** – Conduct large-sample studies that include novices, track skill retention over time, and benchmark against tablet/PC baselines; employ knowledge-distillation techniques to keep on-device AI efficient.

- **Broaden material and machine coverage** – Extend XR support from FDM/LPBF to SLA/SLS printers, elastomeric resins and hybrid CAD projects, while ensuring the framework remains headset-agnostic and open-source.

By heeding these guidelines and tackling the highlighted limitations, researchers and practitioners can move beyond isolated prototypes toward robust, ethical and sustainable AR-enhanced additive-manufacturing ecosystems that deliver measurable productivity gains and a broader societal impact.

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