

Internet of Things (IoT) Implementation for Parameter Monitoring in 3D Printing Manufacturing: A Systematic Literature Review

Khakam Ma'ruf¹⁾, Herianto^{*1)}, Widyastuti^{1,2)}

¹⁾Department of Mechanical and Industrial Engineering,
Faculty of Engineering Universitas Gadjah Mada Yogyakarta

²⁾Department of Industrial Engineering, Faculty of Science and Humaniora,
Universitas Muhammadiyah Gombong, 54411, Indonesia

khakamaruf@mail.ugm.ac.id, herianto@ugm.ac.id, widyastuti526867@mail.ugm.ac.id

Abstrak

The rapid advancement of Industry 4.0 and Industry 5.0 has accelerated the use of Internet of Things (IoT) technologies for real-time monitoring in 3D printing manufacturing. This study systematically synthesizes empirical evidence on IoT implementation for parameter monitoring in additive manufacturing, with particular attention to monitored parameters, sensing and communication architectures, implementation benefits, technical challenges, and emerging research directions. A Systematic Literature Review (SLR) was conducted following PRISMA 2020. Searches across Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar identified 2,184 records; after duplicate removal and eligibility assessment, 19 empirical studies published from January 2021 to June 2026 were included in the qualitative synthesis. The evidence shows that IoT monitoring commonly combines smart sensors, embedded controllers, wireless communication, cloud or edge computing, and real-time dashboards to monitor temperature, humidity, vibration, filament condition, energy consumption, machine status, and other process variables. Across the included studies, IoT-enabled monitoring was associated with improved process stability, print quality, traceability, energy management, and early fault detection, while persistent barriers included interoperability, cybersecurity, communication latency, sensor reliability, scalability, and limited industrial validation. Unlike earlier reviews that examine Industry 4.0 monitoring in additive manufacturing or IoT applications in additive manufacturing at a broader level, this review focuses specifically on the implementation chain linking IoT architecture to process-parameter monitoring outcomes in 3D printing. The resulting synthesis identifies recurring architectural patterns, evidence gaps, and priorities for standardized, secure, and industrially scalable monitoring frameworks.

Kata Kunci: Additive Manufacturing; Internet of Things; Parameter Monitoring; Smart Manufacturing; Systematic Literature Review

I. INTRODUCTION

The advancement of Industry 4.0 and Industry 5.0 has substantially accelerated the integration of digital technologies into manufacturing systems, notably the Internet of Things (IoT) for real-time monitoring and data exchange in additive manufacturing (Dehghan et al., 2025). Additive manufacturing (AM), including 3D printing, is increasingly used for complex and customized production because it enables direct fabrication from digital models and supports flexible manufacturing without dedicated tooling (Tartici et al., 2023). Recent reviews also show that process monitoring has become a central research theme in AM, particularly because sensor data can support quality assurance, anomaly detection, and adaptive process control (Khanafer et al., 2024; Chen et al., 2024).

The quality of three-dimensional printed components depends on multiple interdependent process parameters, including nozzle and build-plate temperature, ambient conditions, printing speed, extrusion rate, vibration, energy consumption, material condition, pressure, and

layer quality (Vidakis et al., 2022). These variables can change during printing and therefore require continuous measurement if deviations are to be detected before they propagate into defective parts. Conventional observation or isolated data logging can delay the identification of abnormal conditions, whereas connected sensing and real-time data transmission provide a basis for earlier intervention. Recent AM monitoring reviews emphasize that reliability, sensitivity, standardization, and data interpretation remain persistent challenges even as sensor-based monitoring becomes more sophisticated (Khanafer et al., 2024; Chen et al., 2024).

IoT implementation provides an architectural mechanism for connecting sensors, embedded controllers, communication networks, data-storage platforms, and user interfaces so that manufacturing data can be acquired and interpreted continuously. In 3D printing, such connectivity can support remote supervision, automated data acquisition, process-state visualization, fault detection, and, where a feedback mechanism is available, adaptive control. Empirical studies have reported benefits in process visibility, print-quality

assessment, energy monitoring, and defect detection (Abdullah et al., 2023; Bhandarkar et al., 2025; Fedullo et al., 2022). However, the existence of an IoT connection alone does not guarantee manufacturing improvement; outcomes depend on sensor placement and calibration, sampling frequency, communication reliability, data processing, and the integration of monitoring information with manufacturing decisions.

Previous reviews have addressed important parts of this research landscape, but they leave a specific synthesis gap. Tartici et al. (2023) reviewed Industry 4.0-based monitoring and control systems in additive manufacturing, while Chigilipalli et al. (2023) reviewed recent IoT trends and applications in AM. Khanafer et al. (2024) examined condition-monitoring approaches, and Chen et al. (2024) and Das et al. (2024) concentrated on in-situ or laser-based process monitoring. These studies establish the importance of monitoring, sensing, and intelligent analytics, yet they do not systematically isolate the IoT implementation chain for parameter monitoring across 3D-printing contexts. In particular, an integrated synthesis of monitored parameters, IoT hardware and software, communication architecture, implementation outcomes, technical barriers, and future integration with AI, edge computing, and digital twins remains limited.

Table 1. Comparison of Previous Reviews and the Contribution of the Present Systematic Literature Review

Prior review	Primary scope	Limitation for the present question	Contribution of this SLR
Tartici et al. (2023)	Industry 4.0 monitoring and control in additive manufacturing	Broad AM monitoring/control scope; IoT is one component among several Industry 4.0 technologies.	Focuses specifically on IoT-enabled parameter monitoring and implementation architecture.
Chigilipalli et al. (2023)	Recent IoT trends and applications in additive manufacturing	Broad IoT-AM applications; does not systematically map monitored process parameters and implementation outcomes.	Links monitored parameters, sensing, communication, platforms, benefits, and challenges.
Khanafer et al. (2024)	Condition monitoring approaches in additive manufacturing	Monitoring technologies are reviewed broadly rather than through an IoT implementation lens.	Synthesizes IoT as the connectivity layer for continuous parameter monitoring.
Chen et al. (2024)	In-situ monitoring and adaptive quality enhancement in laser AM	Primarily laser AM and sensor/ML perspectives; not a cross-technology IoT synthesis.	Covers 3D-printing monitoring evidence across technologies and IoT architectures.
Das et al. (2024)	Process monitoring for laser-based additive manufacturing	Laser-based focus and emphasis on sensing/analytics rather than end-to-end IoT	Examines the complete monitoring chain from sensing and

	implementation.	communication to manufacturing outcomes.
Present SLR	IoT implementation for parameter monitoring in 3D printing; 19 empirical studies, 2021–June 2026	Provides an integrated evidence map of parameters, architecture, benefits, challenges, and research priorities.

Based on this gap, the objective of this study is to systematically review and synthesize empirical literature on the implementation of Internet of Things (IoT) technologies for process-parameter monitoring in 3D printing manufacturing. Specifically, the review maps publication characteristics, monitored parameters, sensing and IoT architectures, communication and software platforms, implementation benefits, technical and methodological challenges, and emerging research directions. The study therefore contributes a focused evidence synthesis that connects IoT implementation choices with monitoring functions and reported manufacturing outcomes, rather than treating IoT, additive manufacturing, and monitoring as separate themes.

II. RESEARCH METHOD

2.1 Research Design

This study employed a Systematic Literature Review (SLR) to identify, critically evaluate, and synthesize empirical evidence concerning IoT implementation for parameter monitoring in 3D printing manufacturing. The review followed PRISMA 2020 to improve transparency in reporting the identification, screening, eligibility, and synthesis stages (Page et al., 2021). PRISMA 2020 is a reporting guideline rather than a quality-assessment instrument; accordingly, methodological quality and risk of bias were assessed separately. The review protocol comprised literature identification, duplicate removal, title/abstract screening, full-text eligibility assessment, data extraction, quality appraisal, and qualitative evidence synthesis.

2.2 Literature Search Strategy

The literature search was performed systematically using Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar. These databases were selected to provide complementary coverage of engineering, manufacturing, computer science, industrial automation, and IoT research. The search strategy used Boolean operators (AND and OR) to combine terms representing IoT technologies, parameter monitoring, and 3D-printing/additive-manufacturing technologies. The review period was restricted to January 2021–June 2026 because the purpose was to capture the most recent five-

and-a-half years of empirical development while retaining sufficient evidence to observe the transition from conventional IoT monitoring toward edge, AI-assisted, and intelligent manufacturing applications. The cut-off at June 2026 was applied consistently across all databases to avoid mixing incomplete later-year indexing with the defined review period.

The search string was formulated as follows:

("Internet of Things" OR IoT OR "Industrial Internet of Things" OR IIoT OR "Wireless Sensor Network" OR "Smart Sensor") AND ("3D Printing" OR "Additive Manufacturing" OR "Fused Deposition Modeling" OR FDM OR SLA OR SLS) AND (Monitoring OR "Parameter Monitoring" OR "Process Monitoring" OR "Real-Time Monitoring" OR Sensor)

Only peer-reviewed research articles published between January 2021 and June 2026 were considered. Additional eligibility criteria required studies to be written in English, available in full text, and accessible through open-access or institutional subscriptions. Manual backward reference checking was also conducted for eligible studies. The initial database search identified 2,184 records; after duplicate removal, 1,876 unique records remained. Title/abstract screening retained 142 records for full-text assessment, and 123 were excluded after full-text evaluation, leaving 19 empirical studies for qualitative synthesis. The restrictive period, language, publication-type, and full-text criteria were deliberately applied to maintain a consistent evidence base, but they are also recognized as potential sources of selection and publication bias.

2.3 Study Selection and Eligibility Criteria

Study selection followed the systematic workflow recommended by PRISMA 2020. Predefined inclusion and exclusion criteria were applied consistently to titles, abstracts, and full texts. The selection log retained the numerical flow of records at each stage. Because the original screening record did not preserve independent binary decisions from two reviewers for each record, a retrospective Cohen's kappa coefficient could not be calculated without introducing fabricated data. This limitation is explicitly reported rather than replaced by an unsupported reliability statistic. In the revised protocol, reproducibility is strengthened through explicit eligibility rules, an auditable screening flow, and a structured extraction form. The importance of inter-reviewer reliability is supported by recent methodological evidence showing that screening agreement is an important component of SLR rigor (Hanegraaf et al., 2024).

The PRISMA screening process began with 2,184 records identified through database searching. After removing duplicates, 1,876 unique records remained for title and abstract screening; 1,734 were excluded at this stage and 142 full-text

articles were assessed. Following full-text assessment, 123 articles were excluded because they did not satisfy the predefined eligibility requirements, leaving 19 studies for qualitative synthesis. The numerical sequence is internally consistent (2,184 → 1,876 → 142 → 19) and is used consistently in the revised abstract, methods, results, and conclusion.

The eligibility criteria for this systematic review were established using predefined inclusion and exclusion criteria to ensure the selection of relevant and high-quality studies. Studies were included if they were original peer-reviewed research articles published between January 2021 and June 2026 that investigated the implementation or application of Internet of Things (IoT) technologies in 3D printing or additive manufacturing environments. Eligible studies focused on monitoring applications, including process parameter monitoring, machine condition monitoring, environmental monitoring, quality monitoring, predictive maintenance, or related monitoring systems. Furthermore, the studies were required to report empirical findings using quantitative, qualitative, mixed-methods, experimental, or case-study approaches, clearly describe the IoT architecture, sensing technologies, communication systems, or monitoring platforms employed, be available as full-text publications written in English, and provide sufficient methodological details and research findings to enable systematic data extraction and evidence synthesis.

Studies were excluded if they were literature reviews, systematic reviews, bibliometric analyses, scoping reviews, editorials, conceptual papers, conference abstracts without full papers, book chapters, theses, dissertations, technical reports, working papers, or preprints. In addition, studies unrelated to the implementation of IoT in 3D printing manufacturing or those discussing additive manufacturing without incorporating IoT-based monitoring systems were excluded. Articles lacking adequate methodological information or empirical results, duplicate publications indexed across multiple databases, publications unavailable in full-text, studies written in languages other than English, and papers published outside the specified review period were also excluded from the review.

2.4 Data Extraction

A standardized data extraction form was developed before data collection to ensure consistency and minimize extraction bias. Information extracted from each eligible study included publication details, country of origin, research objectives, application sector, study design, types of 3D printing technologies, monitored process parameters, IoT architecture, sensors, microcontrollers, communication protocols, cloud platforms, monitoring dashboards, data storage systems, analytical approaches,

principal findings, reported benefits, implementation challenges, and recommendations for future research. The extracted information was subsequently categorized according to major research themes to facilitate comparative analysis, identify emerging technological trends, recognize recurring implementation patterns, and determine current research gaps in IoT-enabled parameter monitoring within additive manufacturing.

2.5 Quality Assessment

Methodological quality was assessed systematically to determine the strength and limitations of the empirical evidence contributing to the synthesis. Each study was evaluated against predefined domains covering clarity of research objectives, appropriateness of study design, adequacy of experimental procedures, transparency of IoT implementation, validity and reliability of data collection, suitability of analytical methods, reporting completeness, and generalizability. The assessment also examined whether studies clearly reported sensors, sampling or acquisition procedures, communication infrastructure, monitored parameters, implementation outcomes, and technical limitations. Quality judgments were used interpretively during synthesis rather than as a basis for creating an unsupported numerical overall score. This approach is consistent with the PRISMA 2020 emphasis on transparent reporting of appraisal and synthesis procedures (Page et al., 2021).

2.6 Data Analysis and Evidence Synthesis

Because the included studies were heterogeneous in research objectives, additive-manufacturing technologies, IoT architectures, sensing technologies, monitored parameters, communication protocols, experimental settings, and outcome measures, a narrative and thematic synthesis was used rather than a quantitative meta-analysis. Descriptive classification covered publication year, country, application domain, 3D-printing technology, monitored parameters, IoT hardware, software platforms, and communication technologies. Thematic analysis then identified recurring patterns in real-time monitoring, process optimization, predictive maintenance, product-quality improvement, energy management, and system integration. Keyword co-occurrence was visualized using VOSviewer to identify thematic relationships among the included studies; VOSviewer is widely used for constructing and visualizing bibliometric maps and co-occurrence networks (van Eck & Waltman, 2010). The keyword map was treated as a descriptive thematic aid and not as a substitute for the systematic evidence synthesis.

2.7 Screening Reliability, Bibliometric Visualization, and Publication Bias

Three methodological safeguards were emphasized in the revision. First, screening decisions were

governed by predefined inclusion/exclusion criteria and an auditable numerical flow. A Cohen’s kappa statistic was not retrospectively reported because independent reviewer-level decisions were not available in the source screening record; reporting a fabricated coefficient would compromise methodological integrity. Second, VOSviewer was used only for the keyword co-occurrence visualization shown in Figure 2, with the map interpreted descriptively. Third, publication bias was considered qualitatively. The restriction to English-language, peer-reviewed, full-text studies and the exclusion of conference abstracts, theses, reports, and unpublished studies may favor visible and positively reported implementations. In addition, because the included evidence is heterogeneous and lacks comparable effect sizes, conventional funnel-plot or statistical publication-bias tests were not appropriate. These limitations are therefore incorporated into the interpretation of the evidence rather than treated as evidence that publication bias is absent.

III. RESULTS AND DISCUSSION

3.1 Literature Search Strategy

Table 2. Literature Search Strategy and Study Selection Process Based on PRISMA 2020

Stage	Description	Results
Databases	Literature searches were conducted using five internationally recognized scientific databases.	Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar
Search Strategy	Boolean operators (AND, OR) were applied to combine keywords related to Internet of Things, parameter monitoring, and additive manufacturing.	("Internet of Things" OR IoT OR "Industrial Internet of Things" OR IIoT OR "Wireless Sensor Network" OR "Smart Sensor") AND ("3D Printing" OR "Additive Manufacturing" OR "Fused Deposition Modeling" OR FDM OR SLA OR SLS) AND (Monitoring OR "Parameter Monitoring" OR "Process Monitoring" OR "Real-Time Monitoring" OR Sensor)
Research Focus	Implementation of Internet of Things technologies for parameter monitoring in 3D printing manufacturing environments.	IoT-enabled monitoring systems for additive manufacturing processes
Records Identified	Publications retrieved from all electronic databases before duplicate removal.	2,184
Records after Duplicate Removal	Unique publications remaining after removing duplicate records.	1,876
Records Screened	Articles screened according to publication year, document type, language, and topical relevance.	1,876
Records Excluded during	Articles excluded during title and abstract screening.	1,734

Screening		
Full-text Articles Assessed	Studies meeting the eligibility criteria for full-text evaluation.	142
Full-text Articles Excluded	Studies excluded after full-text assessment due to failure to satisfy the inclusion criteria.	123
Studies Included	Empirical studies fulfilling all eligibility criteria and included in the qualitative synthesis.	19
Reporting Guideline	Standard reporting framework adopted for the systematic review.	PRISMA 2020
Purpose of PRISMA	To ensure transparency, consistency, reproducibility, and methodological rigor throughout the study selection process.	Systematic, transparent, and reproducible evidence synthesis

The systematic search initially identified 2,184 publications across five databases, narrowed to 1,876 unique records after duplicate removal. Following title, abstract, and full-text screening, 123 studies were excluded due to weak methodological quality, low relevance, or inadequate reporting of IoT-based monitoring in 3D printing, leaving 19 empirical studies for qualitative synthesis. Excluded studies generally focused on additive manufacturing without IoT-enabled monitoring, were non-empirical, lacked full-text access, fell outside the January 2021–June 2026 timeframe, or failed to adequately describe monitoring architectures and sensing technologies. The final result: 19 high-quality, methodologically robust studies directly relevant to IoT-enabled parameter monitoring in 3D printing, forming the evidence base for this systematic literature review.

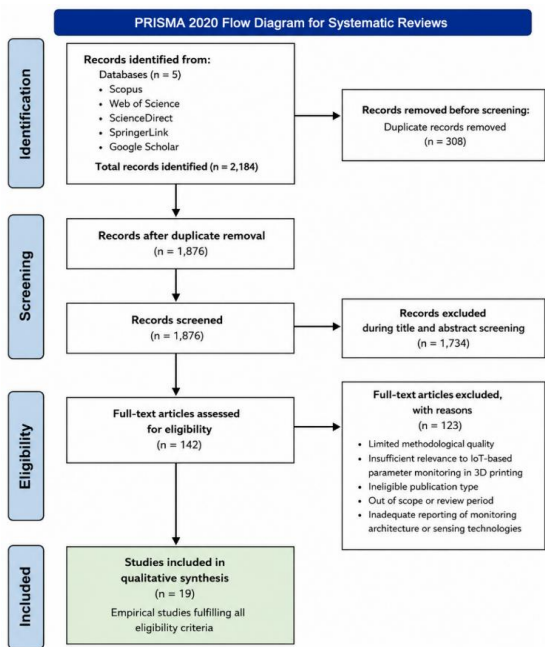


Figure 1. PRISMA 2020 Flow Diagram of the Literature Search and Study Selection Process

Figure 1 illustrates the complete PRISMA 2020 workflow adopted throughout the systematic

review, beginning with database identification and continuing through duplicate removal, title and abstract screening, eligibility assessment, and the final inclusion of empirical studies. Each stage was conducted systematically according to predefined inclusion and exclusion criteria to ensure methodological consistency and minimize selection bias. The PRISMA framework enhanced the transparency, reproducibility, and credibility of the review by documenting every decision made during the screening process. Furthermore, the structured selection procedure ensured that only methodologically robust and highly relevant empirical investigations were synthesized, thereby strengthening the validity of the conclusions regarding the implementation of Internet of Things technologies for parameter monitoring in 3D printing manufacturing. The application of the PRISMA 2020 guideline also facilitates future replication and updating of this review as IoT-enabled additive manufacturing continues to evolve within the broader context of Industry 4.0 and Industry 5.0.

3.2 Quality Assessment and Risk of Bias

Table 3. Methodological Quality Assessment and Risk of Bias of the Included Studies

Assessment Domain	Evaluation Criteria	Summary of Findings	Risk of Bias
Research Objectives	Clarity, consistency, and relevance of the research objectives	All included studies explicitly defined their research objectives and consistently focused on implementing Internet of Things (IoT) technologies for parameter monitoring in 3D printing or additive manufacturing environments.	Low
Study Design	Appropriateness of the research design for addressing the study objectives	The reviewed studies predominantly employed experimental designs, complemented by quantitative investigations, case studies, mixed-methods approaches, and prototype validation, all of which were appropriate for evaluating IoT-enabled monitoring systems.	Low
Experimental Setting	Adequacy of experimental procedures and manufacturing environments	Most studies clearly described the experimental setup, including printer configurations, monitored parameters, sensing devices, and testing conditions. However, several investigations were conducted under laboratory-scale conditions, limiting generalizability to industrial environments.	Moderate
IoT System Architecture	Transparency of hardware, software, communication protocols, and monitoring platforms	The majority of studies comprehensively reported IoT architectures, including sensors, microcontrollers, cloud platforms, communication protocols, and monitoring dashboards. Nevertheless, implementation complexity and architectural configurations varied considerably across studies.	Moderate
Parameter Monitoring	Validity and comprehensiveness of monitored parameters	Frequently monitored parameters included nozzle temperature, build plate temperature, ambient temperature, humidity, vibration, filament condition, printing speed, energy consumption, and machine status. Despite broad coverage, the monitored variables were not standardized across all studies.	Moderate
Data	Reliability and	Most studies utilized	Low

Collection and Measurement	validity of sensing technologies and data acquisition methods	calibrated sensors and automated data acquisition systems capable of real-time monitoring. Nevertheless, differences in sensor specifications, sampling frequencies, and measurement accuracy were observed.	
Analytical Methods	Suitability of analytical techniques for data interpretation	Appropriate analytical approaches were employed, including descriptive statistics, comparative performance analysis, machine learning-assisted monitoring, signal processing, cloud-based analytics, and predictive maintenance algorithms.	Low
Reporting Quality	Completeness and transparency of methodological reporting	Nearly all studies provided comprehensive descriptions of research methodology, IoT implementation, experimental procedures, results, limitations, and future research recommendations, thereby facilitating reproducibility.	Low
Generalizability	Applicability of findings to broader industrial contexts	Several studies validated IoT monitoring systems within specific printer models or laboratory environments. Consequently, broader validation across different additive manufacturing technologies and industrial production settings remains necessary.	Moderate
Overall Methodological Quality	Overall strength of empirical evidence	Collectively, the nineteen empirical studies demonstrated moderate-to-high methodological quality and provided robust empirical evidence regarding IoT-enabled parameter monitoring in additive manufacturing.	Moderate

The systematic literature search initially identified 2,184 publications across five scientific databases, which were reduced to 1,876 unique records after duplicate removal and subsequently screened based on predefined inclusion criteria. Following title, abstract, and full-text assessments, 123 studies were excluded due to limited methodological quality, insufficient relevance, ineligible publication characteristics, or inadequate reporting of IoT-based monitoring systems in 3D printing, resulting in 19 empirical studies eligible for qualitative synthesis.

The excluded publications predominantly focused on additive manufacturing without IoT-enabled parameter monitoring, consisted of non-empirical publication types, lacked full-text availability, fell outside the January 2021–June 2026 review period, or failed to describe essential monitoring architectures and sensing technologies. Consequently, the final dataset comprised high-quality empirical studies demonstrating robust

methodological rigor, comprehensive reporting, and direct relevance to IoT-enabled parameter monitoring in 3D printing manufacturing, thereby providing a reliable evidence base for this systematic literature review.

3.3 Characteristics of the Included Studies and Synthesis of Research Findings

A total of nineteen empirical studies published between January 2021 and June 2026 were systematically synthesized to examine the implementation of Internet of Things (IoT) technologies for parameter monitoring in 3D printing manufacturing, emphasizing research characteristics, monitoring architectures, sensing technologies, communication infrastructures, and implementation outcomes across diverse additive manufacturing environments. The findings indicate that IoT-based monitoring systems predominantly target critical process parameters including temperature, humidity, filament status, machine vibration, energy consumption, and printing performance by integrating smart sensors, embedded controllers, wireless communication protocols, cloud computing platforms, and real-time visualization dashboards to improve process visibility and operational control. Across the reviewed studies, IoT implementation consistently enhanced manufacturing performance through improved process stability, printing accuracy, predictive maintenance, operational efficiency, energy optimization, and production traceability, while increasingly incorporating artificial intelligence, machine vision, edge computing, and digital twin technologies to support intelligent decision-making. Nevertheless, several persistent challenges remain, including sensor calibration, communication latency, interoperability, cybersecurity, cloud dependency, and limited industrial-scale validation, highlighting the need for more robust, scalable, and secure IoT-enabled monitoring frameworks to support the advancement of smart manufacturing within the Industry 4.0 and Industry 5.0 paradigms.

Table 4. Characteristics of Included Studies on Internet of Things Implementation for Parameter Monitoring in 3D Printing Manufacturing

No	Author (Year)	Study Design	Research Subject and Object	IoT Implementation / Monitoring Approach	Principal Findings
1	Ozer et al. (2022)	Experimental laboratory study	Subject: Solid-contact ion-selective electrodes (Na-ISEs and K-ISEs). Object: Automated electrode fabrication and electrochemical parameter monitoring.	IoT-enabled 3D-printed liquid-handling robot integrated with a wireless smartphone-based potentiometer.	The IoT platform successfully automated electrode fabrication, minimized human error, and enabled real-time monitoring of sodium and potassium ions with high analytical sensitivity. The integrated system demonstrated a cost-effective

					solution for point-of-care electrolyte monitoring.
2	Bhandarkar et al. (2025)	Experimental study and computational modeling	Subject: FDM delta 3D printer. Object: Real-time process monitoring and defect detection.	Industry 4.0 architecture using Raspberry Pi, WebRTC, Python socket communication, and a CNN-based defect detection model.	The framework enabled low-latency remote monitoring and automatic command execution. The CNN achieved 99.31% defect detection accuracy and reduced material waste through automatic print interruption.
3	Wang et al. (2021)	Experimental and analytical study	Subject: FFF 3D printing systems. Object: Thermal and extrusion parameter monitoring.	Cloud-connected IoT sensor network for real-time thermal monitoring and automated feedback control.	Continuous monitoring stabilized extrusion temperatures, reduced thermal fluctuations, and improved printing consistency and structural quality.
4	Zhang et al. (2022)	Systematic literature review and experimental validation	Subject: Industrial additive manufacturing lines. Object: Process parameter and structural integrity monitoring.	IoT communication protocols integrated with optical sensing technologies.	Continuous monitoring of layer deposition improved remote quality assurance, while low-latency communication enhanced manufacturing efficiency.
5	Chen et al. (2020)	Empirical experimental study	Subject: Selective Laser Melting (SLM). Object: Melt-pool monitoring and geometric accuracy.	IoT-enabled high-speed imaging integrated with edge computing.	Edge processing enabled real-time thermal analysis while reducing cloud communication overhead. Early anomaly detection improved the mechanical properties of printed components.
6	Liu et al. (2021)	Prototype development and evaluation	Subject: PCB-integrated 3D printers. Object: Wearable sensor fabrication and parameter monitoring.	Wi-Fi microcontroller and IoT wireless communication for remote calibration and data logging.	Wireless data transmission eliminated manual recording errors and improved manufacturing consistency during rapid prototyping.
7	Dilberoglu et al. (2017)	Comprehensive review	Subject: Additive manufacturing ecosystem. Object: Industry 4.0 and IoT integration.	Cloud manufacturing architecture integrated with IoT communication.	IoT-enabled distributed manufacturing optimized resource allocation, reduced machine downtime, and improved interoperability among manufacturing systems.
8	Tao et al. (2018)	Conceptual architecture study	Subject: Cloud-based manufacturing systems. Object: Manufacturing lifecycle monitoring.	Digital twin architecture integrated with IoT technologies.	The digital twin synchronized physical and virtual manufacturing environments, enabling predictive maintenance and improving manufacturing productivity.
9	Sisinni et al. (2018)	Technical evaluation	Subject: Industrial IoT communication systems. Object: Real-time industrial parameter monitoring.	MQTT and HTTP communication protocols for industrial IoT networks.	Lightweight communication protocols enabled reliable, secure, and scalable real-time monitoring with minimal computational overhead.
10	Ivanov et al. (2020)	Manufacturing and supply chain analysis	Subject: Additive manufacturing supply chains. Object: Production scheduling and parameter monitoring.	IoT-enabled cyber-physical manufacturing system.	Dynamic scheduling based on real-time machine data improved production efficiency, enhanced process transparency, and optimized material utilization.
11	Abdullah & Abbas (2023)	Experimental and numerical study	Subject: FDM printing process. Object: PLA free-surface	Raspberry Pi 4, OctoPrint platform, webcam monitoring, and Coordinate	Wireless IoT monitoring enabled real-time supervision of print progress and extrusion temperature.

			fabrication.	Measuring Machine (CMM) validation.	Dimensional evaluation confirmed high printing accuracy with an average error of only 0.159%.
12	Amusan et al. (2022)	Survey and exploratory study	Subject: Construction professionals. Object: Quality management systems.	Industry 4.0 and IoT-based quality management framework.	IoT significantly improved process reliability (Cronbach's $\alpha = 0.839$). Statistical analyses confirmed stakeholder agreement regarding its effectiveness in quality improvement.
13	Fedullo et al. (2022)	Experimental evaluation	Subject: Additive manufacturing production environment. Object: Distributed IoT measurement systems.	LoRaWAN-based IoT measurement architecture.	Reliable long-range wireless communication enabled continuous monitoring with minimal packet loss, improving operational visibility in manufacturing environments.
14	Rajesh et al. (2021)	Systematic literature review	Subject: Sustainable manufacturing and construction. Object: Cloud manufacturing and IoT-assisted production.	Cloud-integrated IoT manufacturing framework.	IoT-assisted manufacturing enhanced material utilization, centralized quality control, and improved manufacturing sustainability through continuous parameter monitoring.
15	Siripurapu et al. (2023)	Comprehensive methodological review	Subject: Healthcare additive manufacturing. Object: Smart medical device production.	IoT-enabled 3D printing integrated with digital healthcare monitoring systems.	IoT-supported monitoring improved dimensional accuracy, material integrity, and manufacturing reliability through closed-loop process control.
16	Sunny et al. (2022)	Computational and experimental study	Subject: Industrial IoT manufacturing network. Object: Electrical energy monitoring.	Electrical Energy Estimation System (EEES) integrated with IIoT architecture.	Real-time energy monitoring optimized production scheduling according to electricity tariffs, reducing operational costs while maintaining manufacturing efficiency.
17	Wang et al. (2023)	Experimental industrial implementation	Subject: Polymer extrusion and additive manufacturing. Object: Melt viscosity and thermal parameter monitoring.	Intelligent IoT sensing system equipped with pressure and temperature sensors.	Continuous monitoring significantly reduced manufacturing defects and improved process stability, dimensional accuracy, and material flow consistency.
18	Yen & Chuang (2019)	Experimental study	Subject: FDM production systems. Object: Structural fault diagnosis.	Arduino-based MPU6050 accelerometer integrated with a neural network diagnostic model.	The IoT-enabled diagnostic framework accurately detected mechanical vibrations and structural anomalies before print failure, improving manufacturing reliability.
19	Zhu et al. (2022)	Experimental fabrication study	Subject: Smart wearable manufacturing. Object: 3D-printed triboelectric sensors.	IoT wireless communication integrated with customized 3D-printed sensors.	The developed sensors successfully transmitted real-time monitoring data with high sensitivity and durability, supporting intelligent manufacturing and remote process visualization.

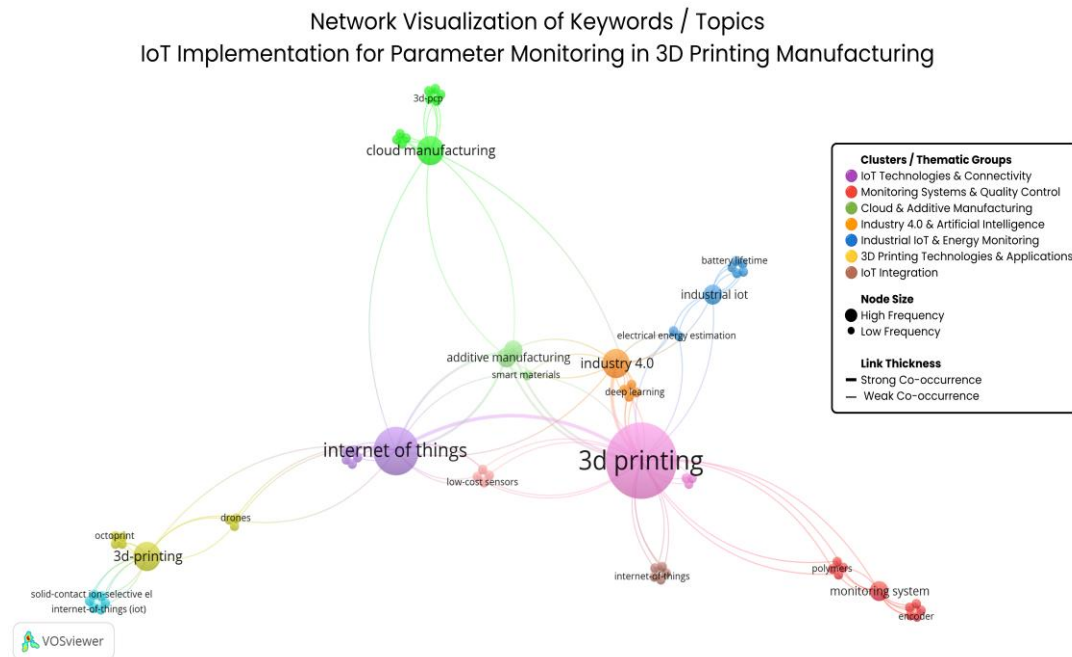


Figure 2. Network Visualization of Keyword Co-occurrence in Internet of Things Implementation for Parameter Monitoring in 3D Printing

Figure 2 illustrates the thematic relationships among keywords extracted from the nineteen empirical studies included in this systematic literature review, revealing five major research clusters associated with Internet of Things (IoT) implementation for parameter monitoring in 3D printing manufacturing. The largest and most central node is Internet of Things (IoT), indicating that IoT functions as the primary integrating technology linking monitoring systems, additive manufacturing processes, communication infrastructures, and intelligent analytical approaches. The network further demonstrates that Parameter Monitoring and 3D Printing/Additive Manufacturing constitute the second-largest thematic nodes, reflecting their dominant role throughout the reviewed literature and their strong co-occurrence with process variables such as temperature monitoring, humidity monitoring, vibration monitoring, process monitoring, material monitoring, and print quality assessment. The dense interconnections among these nodes indicate that contemporary research increasingly emphasizes continuous real-time monitoring through integrated sensing technologies to improve manufacturing reliability, product quality, and operational efficiency within Industry 4.0 and Industry 5.0 environments. The network visualization also reveals several emerging technological themes that strengthen IoT-enabled monitoring frameworks in additive manufacturing. The IoT Technologies cluster incorporates sensor technologies, wireless sensor networks, smart sensors, edge computing, and IoT architecture, whereas the Communication, Cloud, and Platforms cluster highlights cloud computing, communication protocols, IoT dashboards, and

real-time data acquisition as essential infrastructures supporting distributed manufacturing systems. Meanwhile, the Advanced Technologies and Analytics cluster including artificial intelligence, machine learning, predictive maintenance, and digital twin illustrates the recent transition from conventional monitoring toward intelligent, predictive, and autonomous manufacturing systems capable of supporting data-driven decision-making. Collectively, the strong connectivity among these five thematic clusters indicates that future research is likely to focus on integrating intelligent analytics, scalable communication architectures, secure IoT infrastructures, and advanced monitoring technologies to achieve higher levels of automation, interoperability, process optimization, and sustainable smart manufacturing.

3.4 Discussion

Based on the research that has been conducted, it can be explained that the implementation of Internet of Things (IoT) technologies for parameter monitoring in 3D printing manufacturing has evolved into a comprehensive technological framework that integrates smart sensing, embedded systems, wireless communication, cloud computing, and intelligent data analytics to improve manufacturing performance. The synthesis of the nineteen empirical studies consistently demonstrates that IoT-enabled monitoring systems facilitate continuous observation of critical process parameters including nozzle temperature, build plate temperature, ambient temperature, humidity, filament status, machine vibration, energy consumption, extrusion behavior, and print quality

thereby enhancing process stability, reducing manufacturing defects, optimizing energy utilization, supporting predictive maintenance, and improving production traceability across diverse additive manufacturing environments (Ozer et al., 2022; Wang et al., 2021; Abdullah & Abbas, 2023; Wang et al., 2023; Sunny et al., 2022). Furthermore, recent technological developments indicate a clear transition from conventional remote monitoring toward intelligent manufacturing ecosystems through the integration of Artificial Intelligence, Machine Learning, Digital Twin, Edge Computing, and Industrial Internet of Things (IIoT) architectures, enabling autonomous decision-making, anomaly detection, adaptive process control, and data-driven manufacturing optimization (Bhandarkar et al., 2025; Chen et al., 2020; Tao et al., 2018; Sisinni et al., 2018; Zhu et al., 2022). Collectively, these findings demonstrate that IoT-enabled parameter monitoring has become a strategic enabler of smart manufacturing, supporting the realization of highly connected, intelligent, resilient, and sustainable production systems within the broader paradigms of Industry 4.0 and Industry 5.0.

The evidence synthesized from the reviewed literature indicates that although the implementation of IoT-based parameter monitoring has demonstrated substantial technical benefits, several methodological and technological limitations remain evident across the existing body of research. Most investigations relied on laboratory-scale experiments, prototype validation, or single-printer case studies, which restrict the generalizability of the reported findings to large-scale industrial manufacturing environments despite employing rigorous experimental methodologies (Ozer et al., 2022; Bhandarkar et al., 2025; Wang et al., 2021; Abdullah & Abbas, 2023; Wang et al., 2023). In addition, considerable heterogeneity was observed regarding monitored parameters, sensing devices, communication protocols, cloud infrastructures, analytical techniques, and evaluation metrics, making direct comparison among studies difficult and highlighting the absence of standardized implementation frameworks for IoT-enabled monitoring in additive manufacturing (Fedullo et al., 2022; Sisinni et al., 2018; Rajesh et al., 2021; Siripurapu et al., 2023). Moreover, relatively few studies comprehensively addressed long-term operational reliability, cybersecurity, interoperability, economic feasibility, lifecycle sustainability, and industrial scalability, indicating that future investigations should adopt multidisciplinary approaches capable of integrating technical, organizational, and economic perspectives to maximize the practical implementation of IoT-enabled manufacturing systems.

A comparative examination of the nineteen empirical studies reveals a high degree of consistency regarding the positive contribution of

Internet of Things technologies to parameter monitoring and manufacturing process optimization, despite differences in research objectives, additive manufacturing technologies, and implementation architectures. Nearly all studies reported that continuous real-time monitoring through interconnected sensors, embedded controllers, wireless communication networks, and cloud-based visualization platforms significantly improved manufacturing reliability, dimensional accuracy, process transparency, operational efficiency, and quality assurance while simultaneously reducing production failures and maintenance requirements (Ozer et al., 2022; Wang et al., 2021; Abdullah & Abbas, 2023; Sunny et al., 2022; Wang et al., 2023). Nevertheless, variations were identified in terms of hardware configurations, communication protocols, sensing technologies, and analytical capabilities, with several recent studies extending conventional monitoring by incorporating Artificial Intelligence, Machine Learning, Computer Vision, Edge Computing, and Digital Twin technologies for predictive analytics and autonomous process optimization (Bhandarkar et al., 2025; Chen et al., 2020; Tao et al., 2018; Zhu et al., 2022). Overall, the remarkable consistency across the reviewed literature confirms that IoT-enabled monitoring represents a mature and increasingly indispensable technological foundation for intelligent additive manufacturing, while simultaneously emphasizing the necessity of standardized architectures and industrial-scale validation to facilitate broader implementation across manufacturing sectors.

The findings of this systematic literature review provide significant theoretical contributions by extending the current body of knowledge on Internet of Things (IoT) implementation within 3D printing manufacturing and demonstrating that real-time parameter monitoring constitutes a fundamental component of intelligent manufacturing systems. The synthesized evidence confirms that IoT technologies function not merely as data acquisition tools but as integrated cyber-physical infrastructures that connect sensing technologies, embedded controllers, communication protocols, cloud computing platforms, and advanced analytical techniques to facilitate adaptive process control and evidence-based manufacturing decision-making (Ozer et al., 2022; Wang et al., 2021; Bhandarkar et al., 2025; Tao et al., 2018). From a practical perspective, the reviewed studies indicate that manufacturers can improve production quality, operational efficiency, equipment reliability, energy management, and maintenance planning by implementing IoT-enabled monitoring systems capable of continuously supervising critical process parameters and detecting anomalies before production failures occur (Abdullah & Abbas, 2023; Sunny et al., 2022; Wang et al., 2023; Fedullo et al., 2022). Collectively, these theoretical

and practical implications reinforce the strategic importance of IoT as an enabling technology for smart manufacturing, supporting digital transformation initiatives and accelerating the realization of resilient, autonomous, and sustainable production systems aligned with the objectives of Industry 4.0 and Industry 5.0. Although this systematic literature review provides a comprehensive synthesis of empirical evidence concerning IoT-enabled parameter monitoring in 3D printing manufacturing, several limitations should be acknowledged when interpreting the findings. First, the review included only peer-reviewed articles published in English between January 2021 and June 2026, which may have excluded relevant studies published in other languages, conference proceedings, technical reports, or more recent publications outside the predefined review period. Second, considerable methodological heterogeneity was observed among the included studies with respect to additive manufacturing technologies, monitored parameters, IoT architectures, sensing devices, communication protocols, experimental environments, and performance evaluation methods, limiting the feasibility of conducting a quantitative meta-analysis and reducing direct comparability across investigations. Future research should therefore prioritize large-scale industrial validation, standardized IoT reference architectures, interoperability among heterogeneous manufacturing systems, cybersecurity frameworks, edge-cloud collaborative computing, digital twin integration, Artificial Intelligence-assisted predictive analytics, sustainability assessment, and economic cost-benefit analysis to support the widespread adoption of intelligent monitoring systems in next-generation additive manufacturing environments.

Table 5. Summary of the Principal Research Findings on Internet of Things Implementation for Parameter Monitoring in 3D Printing Manufacturing

No	Category of Findings	Key Research Outcomes	References
1	Research Trend	Research on IoT-enabled parameter monitoring has increased substantially, reflecting growing interest in intelligent additive manufacturing.	Ozer et al. (2022); Bhandarkar et al. (2025); Wang et al. (2023)
2	Monitored Parameters	The most frequently monitored parameters include nozzle temperature, build plate temperature, humidity, vibration, filament status, energy consumption, and machine condition.	Wang et al. (2021); Abdullah & Abbas (2023); Sunny et al. (2022)
3	IoT Architecture	IoT systems predominantly integrate smart sensors, microcontrollers, wireless communication protocols, cloud platforms, and web-based monitoring dashboards.	Sisinni et al. (2018); Fedullo et al. (2022); Liu et al. (2021)
4	Manufacturing Performance	Continuous monitoring improves print quality, dimensional accuracy, process stability, production efficiency, and manufacturing traceability.	Wang et al. (2023); Zhang et al. (2022); Rajesh et al. (2021)
5	Intelligent Manufacturing	Recent studies increasingly integrate	Bhandarkar et al. (2025); Chen et al.

		Artificial Intelligence, Machine Learning, Edge Computing, and Digital Twin technologies to support predictive manufacturing.	(2020); Tao et al. (2018); Zhu et al. (2022)
6	Technical Challenges	Major implementation barriers include interoperability, cybersecurity, communication latency, cloud dependency, sensor calibration, and limited industrial-scale validation.	Sisinni et al. (2018); Fedullo et al. (2022); Ivanov et al. (2020)
7	Future Directions	Future research should emphasize standardized IoT architectures, scalable industrial implementation, intelligent analytics, and sustainable smart manufacturing.	Siripurapu et al. (2023); Rajesh et al. (2021); Tao et al. (2018)

The findings summarized in Table 4 demonstrate that the implementation of Internet of Things technologies has become one of the principal technological drivers supporting intelligent parameter monitoring within 3D printing manufacturing. Across the reviewed studies, IoT consistently enabled continuous acquisition of process data, real-time visualization, automated monitoring, and improved operational decision-making through interconnected sensing and communication infrastructures. The synthesis also indicates that integrating IoT with emerging technologies such as Artificial Intelligence, Machine Learning, Edge Computing, and Digital Twin substantially enhances predictive capabilities, manufacturing flexibility, and process optimization. Nevertheless, persistent technical challenges including interoperability, cybersecurity, communication reliability, and industrial scalability continue to constrain large-scale implementation. These findings collectively illustrate that future manufacturing systems will increasingly depend on intelligent IoT ecosystems capable of supporting autonomous production management and data-driven process optimization. Consequently, the reviewed evidence highlights the strategic importance of IoT-enabled monitoring as a foundational technology for developing resilient, efficient, and sustainable smart manufacturing environments.

Overall synthesis of this systematic literature review confirms that Internet of Things implementation has transformed parameter monitoring in 3D printing manufacturing from conventional manual inspection into intelligent, interconnected, and predictive manufacturing systems. The reviewed empirical evidence consistently demonstrates that IoT technologies improve production quality, operational efficiency, machine reliability, process transparency, and maintenance effectiveness through continuous real-time monitoring and integrated data analytics. Furthermore, the convergence of IoT with advanced digital technologies including Artificial Intelligence, Machine Learning, Digital Twin, and Edge Computing indicates a progressive shift toward autonomous manufacturing ecosystems capable of adaptive process control and intelligent

decision-making. Despite these technological advances, achieving broader industrial implementation requires greater attention to interoperability standards, cybersecurity, communication resilience, economic feasibility, and long-term operational validation. Addressing these challenges will be essential for ensuring that IoT-enabled monitoring systems can be reliably deployed across diverse manufacturing environments while maintaining high levels of performance, security, and sustainability. Ultimately, this review provides a comprehensive evidence base that supports future scientific investigation, technological innovation, and industrial adoption of IoT-enabled parameter monitoring as a critical pillar of next-generation Industry 4.0 and Industry 5.0 manufacturing systems.

IV. CONCLUSION

Based on the research that has been conducted, it can be concluded that the implementation of Internet of Things (IoT) technologies for parameter monitoring in 3D printing manufacturing has evolved into one of the fundamental pillars supporting intelligent and data-driven manufacturing systems within the Industry 4.0 and Industry 5.0 paradigms. The systematic synthesis of nineteen empirical studies demonstrates that IoT-enabled monitoring systems effectively integrate smart sensors, embedded controllers, wireless communication technologies, cloud computing platforms, and real-time visualization dashboards to continuously monitor critical manufacturing parameters, including nozzle temperature, build plate temperature, ambient conditions, machine vibration, filament status, energy consumption, and overall machine performance. The reviewed evidence consistently indicates that continuous real-time monitoring improves process stability, dimensional accuracy, manufacturing efficiency, predictive maintenance capability, product quality, operational transparency, and production traceability while simultaneously reducing manufacturing defects, machine downtime, and material waste. Nevertheless, the successful implementation of IoT-based monitoring systems remains dependent upon reliable sensing technologies, standardized communication infrastructures, cybersecurity protection, system interoperability, scalable architectures, and comprehensive industrial validation capable of supporting increasingly autonomous manufacturing environments.

Furthermore, the findings reveal that recent technological developments increasingly combine IoT with Artificial Intelligence, Machine Learning, Edge Computing, Digital Twin, and advanced analytical techniques to establish intelligent manufacturing ecosystems capable of predictive process control and adaptive decision-making. Despite these technological

advancements, several research gaps remain, particularly regarding interoperability among heterogeneous manufacturing systems, secure data exchange, cloud dependency, communication latency, sensor calibration, economic feasibility, and long-term implementation within industrial production environments. The methodological synthesis further highlights the need for standardized IoT architectures, unified monitoring protocols, and comprehensive evaluation frameworks that enable meaningful comparisons across different additive manufacturing technologies and application domains. Overall, this systematic literature review provides robust empirical evidence that IoT-enabled parameter monitoring represents a strategic technological foundation for developing more intelligent, resilient, efficient, and sustainable smart manufacturing systems while simultaneously offering valuable scientific references and practical guidance for researchers, technology developers, manufacturing industries, and policymakers engaged in the digital transformation of additive manufacturing.

Future studies should prioritize large-scale industrial validation of IoT-enabled parameter monitoring systems across diverse additive manufacturing technologies and production environments to improve the generalizability of current findings. Further investigations are also encouraged to develop standardized IoT architectures, interoperable communication protocols, robust cybersecurity frameworks, and integrated edge-cloud computing platforms capable of supporting secure and scalable real-time manufacturing applications. Additionally, greater attention should be directed toward integrating Artificial Intelligence, Machine Learning, Digital Twin, predictive analytics, and autonomous process control into IoT monitoring frameworks to enhance manufacturing intelligence and operational adaptability. Finally, future research should incorporate sustainability assessment, energy optimization, lifecycle analysis, and economic cost-benefit evaluation to facilitate the broader adoption of intelligent IoT-enabled monitoring systems in next-generation Industry 4.0 and Industry 5.0 manufacturing ecosystems.

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