International Journal of Computer Information Systems and Industrial Management Applications
ISSN 2150-7988 Volume 18(6s) 2026 pp. 19-34
https://doi.org/10.70917/ijcisim-2026-2865
Article

The Role of Emerging Information Technologies in Manufacturing Traceability – Trends, Challenges, and Future Directions

Samar Gupta[1], Jitendra Kumar Verma[2]

[1] Indian Institute of Foreign Trade (IIFT), New Delhi, India.
Email: samar_phdmp21@iift.edu
ORCID: 0000-0002-8048-9031
[2] Indian Institute of Foreign Trade (IIFT), Kakinada, Andhra Pradesh, India.
Email: jkverma@iift.edu
ORCID: 0000-0003-4103-4218

Abstract: Industry 4.0 and Information Technology (IT) are nowadays heavily used in manufacturing companies to enhance traceability across entire supply chains. Traceability is a capability of: (i) tracing from where the goods come from, (ii) where they are at a given time, and (iii) how they are used. Therefore, traceability plays a crucial role in terms of efficiency, quality control, and legal requirements.
This paper attempts to investigate the use of IT based traceability systems which are now playing vital role in manufacturing sector. It also attempts to examine the key benefits and obstacles that companies encounter when implementing these systems and what might follow in future. We identify five key trends through expert surveys and a literature survey that are technology adoption, strategic advantages, implementation challenges, industry practices, and future developments. Above led to establish that emerging technologies such as IoT, cloud systems, and AI are now widely spreading as they provide real time information and support data driven decisions making. Nonetheless, tools like ERP and MES are still very popular because they are the core framework of many operations. Meanwhile, blockchain and digital twins are not yet widely adopted due to high costs and integration challenges that are preventing their expansion. This paper also highlights industry-wide differences; however, traceability technologies are adopted more quickly in regulated sectors.
Manufacturers are now also becoming increasingly digitized while tech-companies and regulators are looking to implement better traceability measures. However, there remain huge challenges, such as inadequate technical proficiency, threats of cyber-attacks, unclean data and challenges in sharing data across systems. From these issues, it requires secure, scalable, and intelligent traceability solutions. Going forward, combining the new technology with the old systems will be significant and a well-balanced solution.
Keywords: Emerging Information Technologies, Manufacturing Traceability, Industry 4.0, ERP, MES, IoT, Cloud Computing, Artificial Intelligence, Blockchain.

1. Introduction

Traceability is the ability to trace all elements in the supply chain with the help of recorded information, which can individually identify them, trace the way they travelled or used [14]. All production processes within the manufacturing sector require traceability, from raw material extraction to material component assembly and to final good packaging and distribution [21]. This is required to safeguard against potential litigations, compy to law and even improve quality. Proper control of traceability improves product reliability and effectiveness to ensure product recalls in terms of both standard and regulation compliance and instil confidence in customers. The demand of globalisation for supply chains today has made systems for traceability more complex and vast [13, 23, 28]. There are a huge number of data sources that the system should be able to capture. Traceability systems must evolve into their mature state without sacrificing complete accessibility. Information Technology support for real-time data collection and integration for manufacturing networks, in particular, is through their digital solutions to help make the data capture activities as simplified as possible [11]. Many manufacturers have traditionally integrated Blockchain with Internet of Things (IoT), Manufacturing Execution Systems (MES) and Enterprise Resource Planning (ERP) systems to achieve continuous product tracking throughout its lifecycle [15]. The systems enable manufacturers to enhance their business operations because they provide real-time tracking, recordkeeping and evaluation capabilities for product units, enabling faster decisions, risk control and continuous process enhancement mechanisms. Traceability is now a mandatory requirement for businesses and cannot be ignored. The requirements for traceability systems have evolved because of Industry 4.0. The merger of digital and physical technologies enables highly automated tracking procedures that increase operational excellence and create business competitiveness [3]. Information Technology based traceability systems can be implemented by overcoming various challenges, including high expenses along with data integration issues as well as cybersecurity threats and a need for skilled staff [25]. The paper investigates information technologies effects on manufacturing traceability management while analysing present technological developments and the associated problems along with proposed industrial practice extensions and research avenues.

1.2. The Evolution of Traceability in Manufacturing

The manufacturing industry underwent major enhancements in its traceability implementation during the recent past [26]. Traditionally, the traceability was managed through manual tracking techniques which involved handwritten logs along with paper-based records under conditions prone to human error and delayed processes and restricted accessibility. Organizations that have been using traditional methods found it difficult to identify any inefficiencies in the process, achieve compliance and respond faster to product recall [20]. The dangerous drawbacks of manual approaches had to be addressed because production systems grew complex while quality standards became stricter [9, 13].

Industry 4.0 and Information technologies have enabled faster developments of new technologies [36]. Cloud computing allows easier access to large and scalable datacenters, due to which traceability systems can be quickly adopted [6]. The IoT uses date from various sensors, that allows us to obtain real-time data from devices, goods and logistics systems [19]. Traceability data from various IoT sensors and Artificial Intelligence (AI) enables us to do process optimization, predictive maintenance and h defect detection [34]. The use of blockchain technology can establish open and secure digital records in the supply chain and help stakeholders build trust [29]. Therefore, the industrial traceability has evolved to become both a higher level of operational excellence and a strategic decision-making tool in the modern technology age.

2. Current Trends in Information Technologies for Traceability

Emerging technologies like Blockchain, cloud, AI helped the manufacturing industry in traceability and continuous product quality improvement [10]. Modern IT systems enable intelligent connected environment that can have a bird eye view of entire production and supply chain lifecycle. The real-world improvement of traceability practices emerges from the below trends [5, 14].

2.1 Integration of IoT and Cyber-Physical Systems

Combining Cyber-physical systems with IoT technologies forever shifted how manufacturing companies gather and analyse their data [1]. Manufacturers can now perform elaborate monitoring of parts and equipment activity, as well as environmental conditions, using IoT-enabled smart devices, including RFID tags, smart sensors and edge units that store data and clean it. Though it has become complex, it allows logistics systems and production lines that contain these sensors to continuously monitor a variety of parameters (vibration, temperature, humidity) while monitoring the condition of the machine in real time. By undertaking various predictive maintenance practices at the early stages of manufacturing, manufacturers can minimise downtime and improve product quality [13].

2.2 Adoption of Blockchain for Data Integrity

In the past, researchers have explored the potential of blockchain technology to improve trust and transparency in traceability systems [22, 40]. There are also various known challenges with blockchain including slow performance. Blockchain uses a data ledger that cannot be tempered and thus, it ensures traceability and transparency [13]. This is especially helpful in sectors where product safety and authenticity are crucial and have stringent regulatory and compliance requirements, like automotive, pharmaceuticals, food and beverage, and aerospace. Smart contracts can increase supply chain accountability and operational efficiency by automating various compliance checks.

2.3 Cloud-Based Traceability Platforms

Cloud platforms are very much scalable with the facility remote access. They also have provision of easy data exchange which is need of traceability systems [33, 39]. Cloud-based platforms can be used by businesses, which can sync IoT data from multiple sources to a single cloud, making transactions more transparent and quick [27]. These solutions have advanced extract, transform and cleaning features with the out of the box reporting capabilities which makes fast and informed decisions feasible. SMEs are now able to gain access to advance traceability solutions at reduced upfront expenses due to cloud solutions which do not require heavy investments for on-site infrastructure.

2.4 AI and Predictive Analytics

Data on supply chain and manufacturing operations is often analysed and processed through advanced AI and machine learning tools for predictive modelling and operation improvement [4]. Though these systems can be expensive and difficult to integrate, they can analyse the standard patterns and detect any equipment issues and quality problems early[30]. By correlation of data on several production variables, AI analytical approaches allow for root cause analysis, supply chain optimisation, as well as inventory prediction improvement. The preemptive steps also aid in reducing waste and downtime.

2.5 Digital Twins

A digital twin is a virtual replica of a physical system or product. Information received from IoT hardware and sensors is fed into a system that creates a virtual replica of the production [31]. Various inputs to the system can be changed to simulate the output and understand how the system will behave in various conditions. Digital twins enable manufacturers to test processes and make predictions while not interrupting ongoing work [11]. Digital twins paired with traceability systems enable visualisation and improved performance analysis.

3. Literature review

Liu et.al (2025) identified that the traditional aerospace industry is adopting predictive maintenance [24]. This is also critical due to the nature of the aerospace industry that needs to identify and fix issues proactively. The shift to predictive maintenance will reduce life cycle costs, enhance operational uptime and efficiency, and extend the useful life of various platforms. Data analytics from IoT sensors and its integration with multi-physics modelling has introduced a new model known as the 'Digital Twin.' This digital twin is like a copy of a physical system, that can forecast the future state, while continuously adapting to operational changes based on real-time data and information. The author proposed a general framework for developing a digital twin in conjunction with industrial Internet of Things (IoT) data to support aerospace platforms. It emphasizes the significance of data fusion techniques within the digital twin framework. The raw data can be converted into information for decision making by the fusion of model and sensor data [24].

Sanfiya et.al (2025) analysed the impact of digital twins in the agriculture food production industry for tackling challenges such as malnutrition, food waste, and greenhouse gas emissions [35]. These digital twins are regularly fed with sensor data, which helps to fine-tune behaviour under various conditions. They can make their presence felt in the estimating and prediction of food quality and therefore offer the stakeholders room of manoeuvre in making decisions at the time of the supply chain logistics and storage conditions. Digital twins also enhance supply chain management through complete visibility and traceability. Digital twins play an important role in Industry 5.0 and have been widely researched to mitigate operational risks by increasing human productivity and minimizing physical equipment wear and tear. This research is trying to summarize the current literature and explore the role Industry 5.0 and digital twins can play to promote intelligent automation in various sectors. Because of rapid developments in digital twin technology, its applications will be extended to other industries and use cases.

Attaran et.al (2024) concluded that Digital Twins (DTs) that take input from physical systems, serve as virtual counterparts. Simulation can be done on Digital twins without changing the physical production system. Multiple simulations in various conditions could be tested using DTs by changing the input parameters. However, despite their significant potential, the adoption and utilisation of DTs remain limited as the industry is not able to distinguish DTs from traditional simulation technologies. The study defines the concept of DTs, outlines their development and evolution, reviews the key enabling technologies, and identifies the role of IIoT as the critical mandatory input for DTs. It also examines current trends in DTs, highlights the primary challenges, and explores their applications in the manufacturing process and Industry 4.0.

Ullah et.al (2024) concluded that production systems that are flexible can produce a wide range of products in variable quantities [38]. This results in scheduling and control issues that hamper production optimization by compromising productivity, quality, and energy efficiency. Digital twin technology, as used here, aims to further explain these potential applications [38]. A digital twin using simulation models, data collection, and machine-learning algorithms was produced to mirror the behaviour of an actual production system[38]. This allows informed based decision making and proactive adjustments to get the most out of resources and process efficiency. Various experiments showed that the digital twin improved production system performance significantly, reduced energy consumption and increased productivity as a result[38]. The paper illustrates how digital twins are able to change the approach of smart manufacturing systems for higher production, fewer defects, and energy efficiency [38].

Rane et.al (2023) studied intelligent and sustainable construction methods that have been made possible due coming together of Internet of Things and Artificial Intelligence in the Engineering and Construction sector [32]. This study investigates the difficulties and potential paths for incorporating these technologies in the engineering and construction industry. They emphasised how big data, advanced computing models, and the Internet of Things can improve resource utilization, streamline operations, and improve decision-making. This can be true for all industries. They also demonstrated how Blockchain technology, AI, and IoT can work in cohort to improve transaction security and transparency while promoting sustainable and effective building methods. The placed a strong emphasis on using the Sustainable Development Goals as a framework for future projects in the engineering and construction industry. Therefore, ref. [32] serve as a guide for researchers, industry stakeholders, and policymakers, highlighting the value of creative problem-solving and strategic cooperation in maximizing the potential of AI, IoT, and big data technologies for astute and sustainable engineering and construction practices

Guo et.al (2022) explained how Blockchain technology can enhance transparency, trust, traceability, and efficiency in optimal costs. Thus, blockchain can be a crucial component of business and industrial innovation [12]. However, research on its application in smart manufacturing remains limited. This survey aims to provide theoretical foundations and a summary of current research on the use of blockchain technology in smart manufacturing. It addresses the four main concerns of smart manufacturing- system coordination, trust mechanisms, data security, and data sharing, and evaluates the corresponding blockchain solutions. The survey also identifies issues and potential research directions to improve the application of blockchain technology in smart manufacturing.

Samar et.al (2024) studied how blockchain technology can be used for end-to-end traceability in the automotive industry, enabling the identification of liability for a crash of a self-driving car with trust and transparency [13]. Blockchain also has certain limitation that prevents it from storing large amount of data and the modified storage algorithm was introduced. The study also proposed a blockchain framework for self-driving vehicles, suggested the data that needs to be captured across the automotive lifecycle using IoT sensors and demonstrated experimental use cases. The adoption of cloud technologies is important for achieving agility in the deployment across industry and lower cost of ownership.

Ahmad et.al (2022) studied how blockchain can be used for managing industrial operations. Current systems lack operational transparency, auditability, traceability, security, and trusted data provenance [2]. Due to their fragmented, manual, and centralized nature, many of these systems are vulnerable to manipulation and single points of failure. They highlighted the feasibility of blockchain in the industry with various blockchain-based methods, research projects, business initiatives, and case studies. They discussed systems that automate tasks such as tracking petroleum products, securing international trade documents, and organizing bidding and purchasing processes for oil exploration rights using blockchain-based smart contracts. Additionally, they identified unresolved issues as potential areas for further research.

Jamwal et.al (2021) concluded that Industry 4.0 encompasses data management, manufacturing competitiveness, production processes, and efficiency [17]. Digital twins, IoT, data analytics, and artificial intelligence are some of the most significant enabling technologies. In the UN's Sustainability 2030 agenda, sustainability is recognised as a critical business strategy. The research about these fields is scarce, but Industry 4.0 helps in making business practices more sustainable [17]. Employing a systematic literature review method, this study aims to evaluate the status of existing research and the future prospects associated with Industry 4.0 technologies for manufacturing sustainability [17]. It covers the influence and contributions of different technologies in achieving sustainability in manufacturing with new avenues for research and possibilities for academia and industry.

Table 1: Comparison Table

Author & Year	Focus	Findings	Key Insights
Liu et al. (2025)	Digital Twin in Aerospace Predictive Maintenance	Integration of data-driven analytics with multi-physics modeling to form digital twins; real-time adaptation of physical systems; data fusion (sensor-to-model, model-to-model) plays a critical role.	Digital Twin enables predictive maintenance through continuous data integration and modeling, enhancing operational autonomy and decision-making in aerospace systems.
Sanfiya et al. (2025)	Digital Twin in Agri-food & Supply Chains under Industry 5.0	Real-time sensor-driven digital twins optimize logistics, reduce food waste, and enhance traceability; discussed implications across sectors and link to human-centric Industry 5.0.	Digital Twins can transform food systems and supply chains by enabling intelligent, sustainable, and flexible management solutions aligned with Industry 5.0.
Attaran et al. (2024)	Digital Twin and IIoT in Manufacturing	Defined DTs and their relationship with IIoT; outlined development, enabling technologies, trends, and barriers to adoption; noted overlap with traditional simulations.	While promising, Digital Twins in Industry 4.0 are still emerging, facing adoption barriers and needing to distinguish themselves from conventional simulation tools.
Ullah et al. (2024)	Digital Twin for Flexible Manufacturing Systems (FMS)	Developed a DT-integrated FMS using ML, simulations, and data collection; improved performance metrics—quality by 15.8%, energy efficiency by 13.9%, and productivity by 14.53%.	Demonstrates that Digital Twins can enable real-time optimization and adaptive control in manufacturing, boosting sustainability and operational performance.
Rane et al. (2023)	Integration of AI, IoT, Big Data & Blockchain in AEC Industry	Emphasized potential of smart technologies to improve AEC productivity and sustainability; focused on resource optimization, decision-making, and SDG alignment; highlighted interdisciplinary collaboration.	Adoption of AI, IoT, and blockchain can reshape construction with smarter, greener operations; strategic collaboration and SDG alignment are crucial.
Guo et al. (2022)	Blockchain in Smart Manufacturing	Identified the critical role of blockchain in improving security, transparency, and efficiency; outlined four core challenges: system coordination, trust mechanisms, data security, and limited adoption in smart manufacturing.	Blockchain technology, though underutilized in manufacturing, has great potential to support Digital Twin infrastructure with secure, trusted, and efficient data management and operations.
Samar et al. (2024)	Blockchain in Automotive Manufacturing	Identified a modified storage algorithm for faster storage in blockchain, suggested a	Blockchain is critical to bring trust, traceability and transparency in industrial automotive traceability. A

		blockchain framework for self-driving cars	efficient blockchain framework is needed for faster adoption of technology in the industry.
Ahmad et al. (2022)	Blockchain in Oil & Gas Supply Chain Management	Current systems lack transparency, traceability, and are centralized and error prone. Blockchain can automate operations, enhance document security, and streamline bidding using smart contracts.	Blockchain presents a transformative opportunity for oil and gas supply chains through automation, decentralization, and secure data exchange; many practical applications and research gaps exist.
Jamwal et al. (2021)	Industry 4.0 for Sustainability in Manufacturing	Reviewed current research and future directions in using DTs, AI, IoT, CPS, and big data for sustainable manufacturing; aligned with UN 2030 SDGs; identified research gaps.	Industry 4.0 technologies are pivotal in achieving sustainable manufacturing; more research is needed to understand and scale these technologies for green and competitive industrial practices.

3. Research Methodology

We decided to use a qualitative exploratory research design for this study. This research design provides an in-depth examination of present conditions that incorporates both digital technology integration, related obstacles and predictive developments. We also used expert surveys and academic literature reviews to fulfil the objectives. We combined the approaches to fulfil research objectives through both theoretical concepts and practical implementation methods.

3.1 Research Design

The study adopts a mixed qualitative method to analyse how manufacturing traceability is supported by efficient Information Technologies for an optimal business relevant output. We used resources from academic and industrial institutions worldwide instead of focusing exclusively on one particular industry or geographic location. Thus, the study benefits from wide scope that allows for a better understanding of technology across different manufacturing settings.

3.2 Data Collection Methods

The research used both expert survey with structured and semi-structured questions along with a comprehensive literature review as its primary data collection methods. The research reviewed technical reports together with standards documents, scholarly journals and white papers from manufacturing industries which were published between years 2010 to 2024. The most significant databases during this research included Google Scholar, SpringerLink ScienceDirect and IEEE Xplore. The search terms ‘manufacturing traceability’, ‘ERP systems ‘, ‘IoT in production’, ‘blockchain for supply chain’ and ‘digital twins in manufacturing’ were used to find the required content. The research utilized information from thirty (30) industry experts working in positions such as CIO, Director Operations, Consultant, Directory reporting, excellence head, among others who specialized in automotive and electronics production as well as the food processing and pharmaceutical industries. The survey aimed to understand from their practical use and implementation of traceability system and its associated challenges.

3.3 Data Analysis

Thematic analysis was used to extract important insights from the data collected from survey and literature. We identified significant themes, and categorized into five main areas: future opportunities, system capabilities, implementation challenges, technological integration, and regulatory compliance. The study made sure there was a strong correlation between theoretical claims and real-world industry practices by comparing patterns found in the literature with those obtained from expert survey. This triangulation of data sources gave a comprehensive picture of the state of traceability systems in manufacturing and confirmed the validity of the findings. We used SPSS tool for reliability analysis of collected data. Cronbach alpha was calculated and found to be 0.778. A value of 0.7 to 0.95 is generally considered acceptable [37]. Thus, our survey is found to be of high quality and data can be considered as reliable.

Cronbach's Alpha
.778

We calculated Person correlation between various traceability technologies. We excluded Blockchain technology from analysis because just 1 survey participant mentioned that blockchain was implemented. **Table 2** shows strong positive correlation between Cloud with AI and IoT, suggesting higher cloud adoption of deployment of new technologies. AI and IoT are relatively new technologies and require a scalable infrastructure. Thus, AI and IoT are often built over cloud [8], as cloud offers scalability [16] and flexibility. The results seems to correlate the real world scenario.

Table 1: Person correlation between technologies

		Implemented ERP	Implemented MES	Implemented IoT	Implemented Cloud	Implemented Digital Twins	Implemented AI
Implemented ERP	Pearson Correlation	1	-.134	.231	.143	.175	.058
Implemented MES	Pearson Correlation	-.134	1	.267	.149	.105	.164
Implemented IoT	Pearson Correlation	.231	.267	1	**.342**	.131	.190
Implemented Cloud	Pearson Correlation	.143	.149	**.342**	1	.197	**.459**
Implemented Digital Twins	Pearson Correlation	.175	.105	.131	.197	1	.271
Implemented AI	Pearson Correlation	.058	.164	.190	**.459**	.271	1

3.4 Scope and Limitations

This research offers a comprehensive perspective across different manufacturing sectors and technologies, however, it is limited by several factors. The limitations are (1) Lack of empirical case studies on the use of cutting-edge technologies like blockchain and artificial intelligence in traceability systems, (2) Expert survey responses can be influenced by organizational contexts and individual experiences. However, these drawbacks are minimized and overall robustness of the study is improved by combining primary and secondary data sources and conducting a thorough thematic analysis.

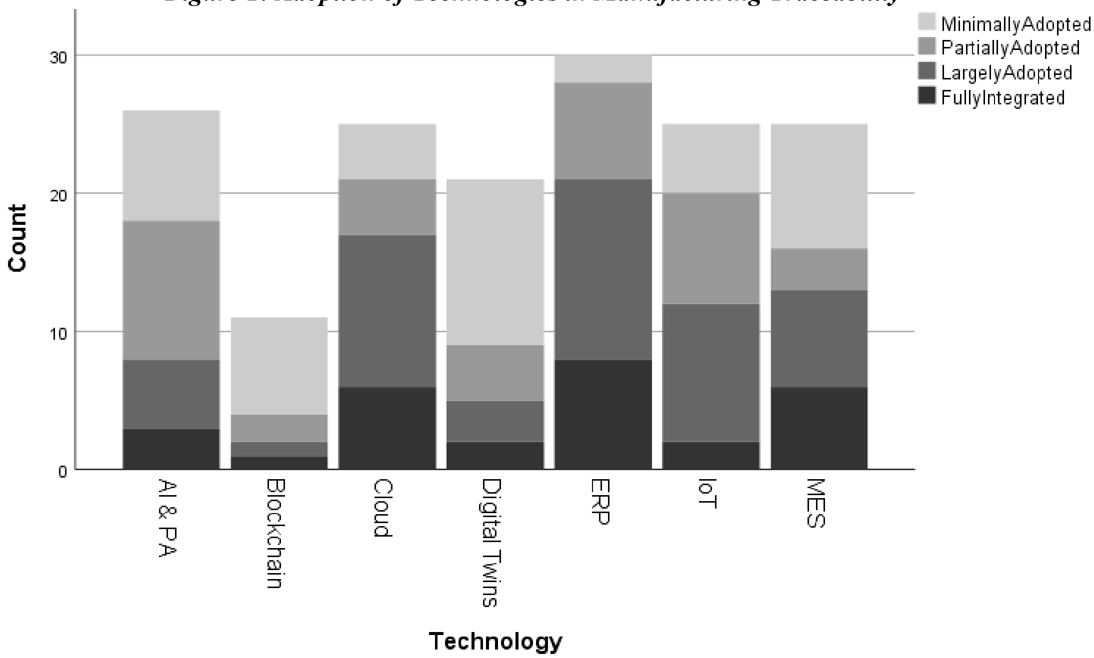
4. Results

The findings are based on expert survey and a thematic analysis of the literature. We have divided findings in to main five categories that are technology adoption, perceived benefits, implementation challenges, industry-specific usage, and future outlook. The overall discussion on results is as follows.

4.1 Technology Adoption in Traceability Systems

According to the analysis, cloud platforms and Artificial Intelligence are the innovations that are being adopted the fastest, while ERP, MES and IoT systems continue to be fundamental technologies. The adoption levels of various technologies in traceability are depicted in Figure 1.

Figure 1: Adoption of Technologies in Manufacturing Traceability



Since ERP systems are essential for integrating and managing manufacturing processes, 81.8% of respondents said they use them frequently, demonstrating the highest level of adoption. The increasing importance of IoT (Internet of things) and MES (Manufacturing Execution Systems) in real-time monitoring and control of production activities is highlighted by their 56.4% and 36.4% adoption rate respectively. The high adoption rates of cloud platforms i.e. 48.4% indicate rising demand for scalable data management solutions and connectivity. With 39.4% adoption, the AI and predictive analytics show a mixed trend that suggests a transitional stage where industries are investigating intelligent insights but have not yet fully incorporated them. On the other hand, digital twins and blockchain have relatively low adoption rates (12.1% and 3.0%, respectively) perhaps because of their more expensive and complex implementations. These trends show how manufacturing sectors differ in terms of organizational preparedness and technological maturity.

4.2 Perceived Benefits of Information Systems based Traceability

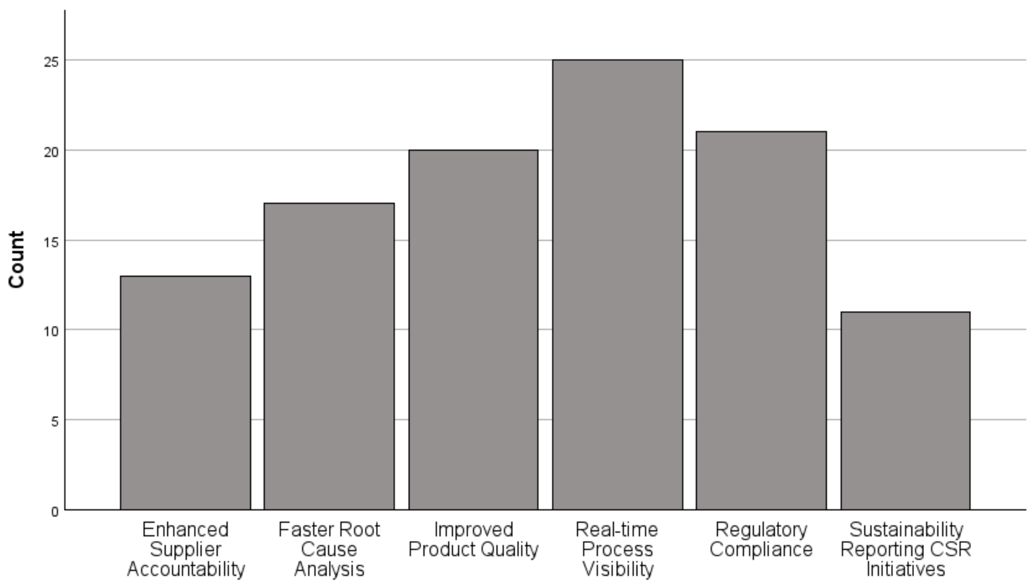
According to participants from various sectors, adoption of Information Systems (IS) based traceability has several strategic and operational advantages. Most frequently mentioned benefits are quality assurance, regulatory compliance, faster root cause analysis and real-time visibility. Table 3 lists the main advantages that respondents with a sample size of thirty (33) have reported. 75.8% of respondents recognized that real-time process visibility as the most frequently mentioned benefit which demonstrates its crucial role in improving operational transparency. Following closely behind, with 63.6% reporting regulatory compliance, this indicates a high priority on following the law and industry standards. 60.6% of respondents mentioned improved product quality, indicating how crucial it is to preserve competitive advantage. 51.5% respondents mentioned faster root cause analysis. 39.4% of participants reported improved supplier accountability which highlight the importance of dependable supplier performance. Finally, 33.3% of respondents acknowledged sustainability reporting which indicates a moderate but increasing interest in CSR and environmental practices. Figure 2 shows the count of various benefits as mentioned by survey participants.

Table 2: Key Benefits Reported by Respondents

	Responses	

		N	Percent	Percent of Cases
Benefits	Benefit Real-time Process Visibility	25	23.4%	75.8%
	Benefit Regulatory Compliance	21	19.6%	63.6%
	Benefit Improved Product Quality	20	18.7%	60.6%
	Benefit Enhanced Supplier Accountability	13	12.1%	39.4%
	Benefit Faster Root Cause Analysis	17	15.9%	51.5%
	Benefit Sustainability Reporting CSR Initiatives	11	10.3%	33.3%
Total		107	100.0%	324.3%

Figure 2: Perceived Benefits of IS-Based Traceability



4.3 Challenges in Implementation

The study found a number of implementation issues. Cost, data integration and lack of skilled personal were cited as the main issues. Particularly, SMEs emphasized infrastructure and financial limitations.

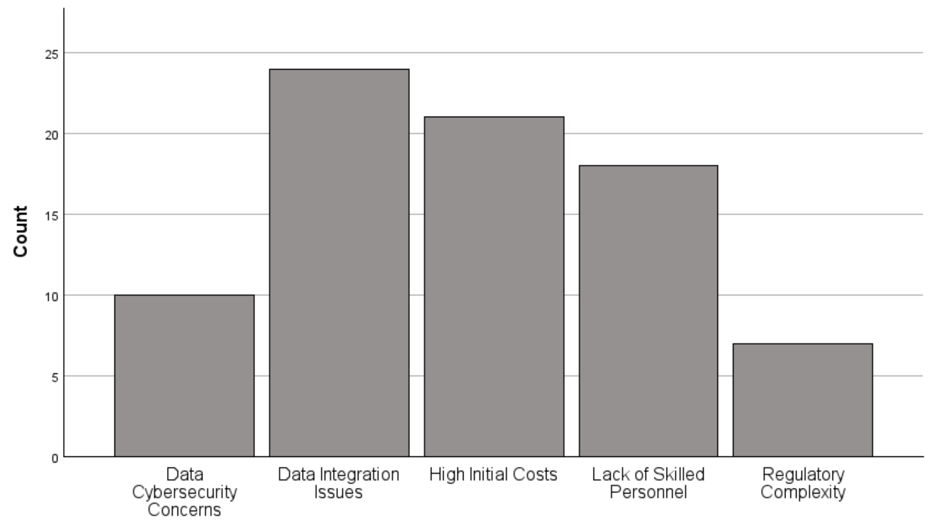
Table 2 lists the main issues that respondents pointed out, based on information from a sample of thirty (33) participants. 32.3% of respondents mentioned Cyber Security Concerns. Just 22.6% of participants mentioned regulatory complexity, highlighting the challenges businesses encounter when attempting to navigate and adhere to changing regulatory environments.

Table 3: Key Challenges Identified by Respondents

		Responses		Percent of Cases
		N	Percent	
Ch	Data Integration Issues	24	30.0%	77.4%

	High Initial Costs	21	26.3%	67.7%
	Data Cybersecurity Concerns	10	12.5%	32.3%
	Lack of Skilled Personnel	18	22.5%	58.1%
	Regulatory Complexity	7	8.8%	22.6%
Total		80	100.0%	258.1%

Figure 3: Key Challenges in Implementing IS-Based Traceability



4.4 Industry-Wise Trends

Different industries have different levels of traceability system adoption. Because of safety and regulatory requirements, the pharmaceutical, chemical, healthcare and automotive industries exhibit the highest levels of adoption, whereas the electronics and consulting report slower adoption.

Table 4: Industry-Wise Integration Levels of IS for Traceability

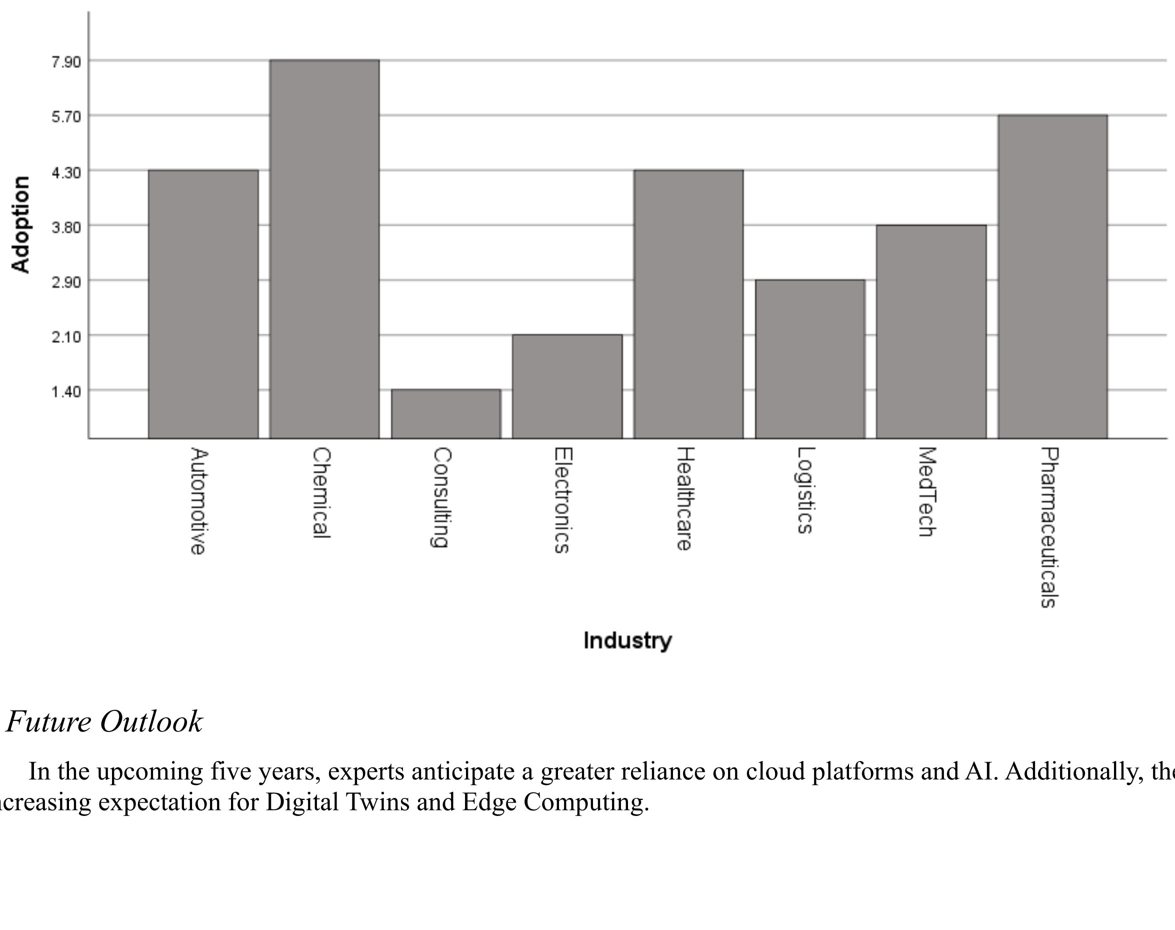
Industry	**Average Adoption Score (out of 10)**
Chemical	7.9
Pharmaceuticals	5.7
Automotive	4.3
Healthcare	4.3
MedTech	3.8
Logistics	2.9
Electronics	2.1

Consulting	1.4

The Information Technologies adoption levels for traceability by industry are shown in Table 5, which shows how much each sector has embraced and integrated IS to guarantee product traceability. We surveyed each participant for 7 technologies namely ERP, MES, IoT, Cloud, Blockchain, Digital Twin, and AI. We considered 1 point for each implemented technology. Sum of these generated an adoption score for each participant with range of 0 to7. Average score was calculated by grouping all participants from same industry and it generated average adoption score of an industry with range of 0 to 7. We then converted the average adoption score from 0-7 range to 0-10 range, for making them easier to read. We have ignored responses from banking, aviation, infrastructure and seafood industries as we received just 1 response from them.

Because of its strict regulations and the vital role traceability plays in guaranteeing safety and compliance, the chemical and pharmaceutical and healthcare industry has the highest average adoption score (7.9 and 5.7 respectively). The automotive industry comes in second with a score of 4.3 each, which shows that quality control and component tracking are highly valued. Next in line with a score of 3.8, Medical Technology demonstrates a strong use of traceability systems. Electronics received a score of 2.1, which indicates a moderate/low degree of integration. Consulting received a score of 1,4 because they are dependent on customer systems and have a lower need of internal traceability systems.

Figure 4: Industry-Wise Adoption Levels of IS for Traceability



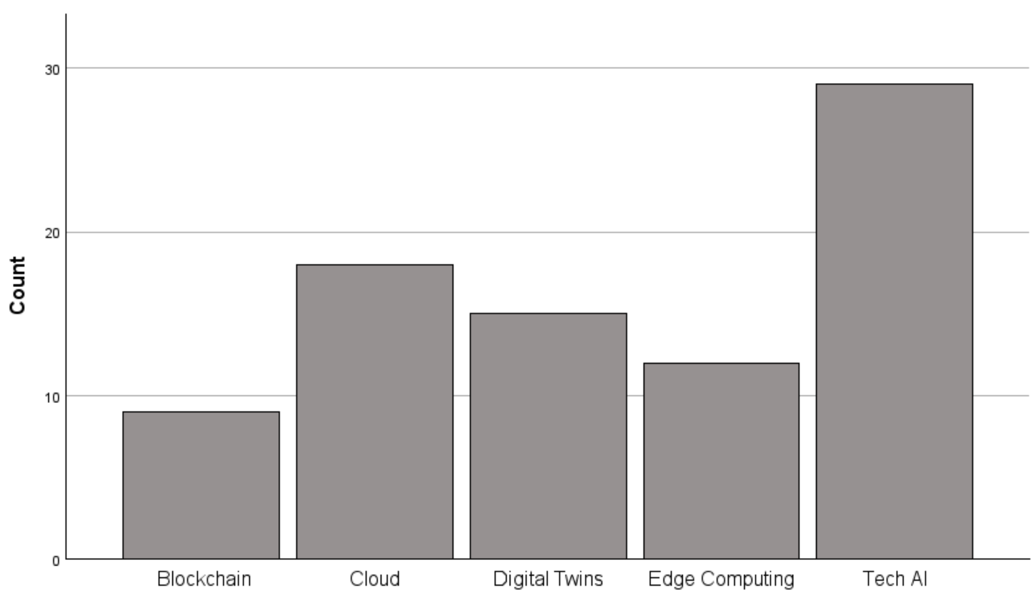
4.5 Future Outlook

In the upcoming five years, experts anticipate a greater reliance on cloud platforms and AI. Additionally, there is increasing expectation for Digital Twins and Edge Computing.

Table 5: Technologies Expected to Grow

		Responses		Percent of Cases
		N	Percent	
Emerging Technology	AI	29	34.9%	87.9%
	Edge Computing	12	14.5%	36.4%
	Blockchain	9	10.8%	27.3%
	Digital Twins	15	18.1%	45.5%
	Cloud	18	21.7%	54.5%
Total		83	100.0%	251.5%

Figure 5: Technologies Expected to Grow in Use Over Next 5 Years



Over the next five years, experts predict that the use of various emerging technologies will increase. These predictions are shown in Table 4. 87.9% of experts predict greater adoption of AI and predictive systems, which are predicted to grow at the fastest rates, according to the table. It is anticipated that Cloud Platforms will expand by 54.5%, indicating a sustained and high growth as cloud computing develops. The use of digital twins, which replicate physical systems virtually, is expected to rise by 45.5% as a result of their use in sectors like manufacturing and healthcare. Edge computing application is predicted to grow by 36.4 of experts due to the growing need for real-time data processing at the network edge. Blockchain technology, which is well-known for its transparency and security features, is predicted to expand slowly by 27.3%, demonstrating its low significance outside of the cryptocurrency space. All things considered, the table shows a significant upward trend in the use of decentralized, agile and intelligent technologies.

4.6 Discussion

In this paper, we have assessed the adoption of IS-based traceability in manufacturing. Five major themes including technology adoption, perceived benefits, implementation challenges, industry-specific trends, and future outlook were identified from expert survey and literature analysis. Findings suggests emerging technologies like the Internet of Things, AI and cloud platforms are quickly gaining traction due to their scalability, reporting, automation and connectivity benefits, while foundational technologies like ERP and MES systems exhibit the highest adoption rates due to their crucial role in operations and real-time monitoring. Emerging technologies like blockchain and digital twins have a lower degree of adoption due to technological complexity and experimental interest. Respondents believed in high strategic and operational value of matured traceability systems due to its benefits including improved real-time visibility, improved regulatory compliance, faster root cause analysis, and higher product quality. Respondents also called out challenges in quick and effective adoption due to high cost for effective integration of large number of data sources and lack of skilled personal. Meanwhile, industry-specific analysis shows that highly regulated industries like pharmaceuticals, chemical and automotive show greater maturity of traceability systems. These results highlight how different industries' adoption of traceability is influenced by different degrees of technological preparedness, regulatory pressure, and resource availability.

4.7 Conclusion

This paper emphasizes that Information Technologies have a profound effect on manufacturing traceability. Matured IT systems are important for improving operational responsiveness, transparency, and quality control. A dynamic shift towards intelligent, agile and data-driven manufacturing environments is reflected in the integration of cutting-edge technologies like Internet of Things, Artificial Intelligence, and Cloud Computing with traditional systems like ERP and MES. This shift is driven by several factors, including organizational readiness, cost, regulatory requirements, complexity, and sector-specific demands. Meanwhile, the strategic and operational adoption of information system-based traceability helps in enhanced real-time visibility, regulatory compliance, improved product quality and quicker root cause analysis. It can be safely concluded that adoption across all industries could be increased by addressing issues with system integration, funding, and technical know-how. Significant differences in adoption rates across industries are also revealed by the proposed study where digital maturity and regulatory pressures are playing a major role. A balanced approach is needed for going forward for making traceability strategies to be successful and utilizing the reliability of current systems while gradually incorporating cutting-edge technologies. Policymakers, technology developers, and industry stakeholders must work together to remove current obstacles and advance scalable, secure, and interoperable solutions. Traceability is becoming more and more important as manufacturing continues to change under the impact of Industry 4.0 to achieve operational excellence, customer trust, and sustainable growth.

Acknowledgement

We would like to express our profound gratitude to Prof. A. R. Singla, the Head of the Computer Centre at Indian Institute of Foreign Trade, New Delhi, for his invaluable guidance, support, and encouragement as a Doctoral Advisory Committee member. His insights and expertise have been instrumental to the success of this work.

Competing Interests

The authors of this publication declare there are no competing interests.

Funding Agency

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. Funding for this research was covered by the first author of the article.

References

1. Abikoye O, Bajeh A, Bamidele A, Oloduowo A, Mojeed H, AbdulRaheem M, Oladipo I, Salihu S (2021) Application of Internet of Thing and Cyber Physical System in Industry 4.0 Smart Manufacturing. pp 203–217

2. Ahmad RW, Salah K, Jayaraman R, Yaqoob I, Omar M (2022) Blockchain in oil and gas industry: Applications, challenges, and future trends. Technology in Society 68:101941. doi: 10.1016/j.techsoc.2022.101941
3. Akter S, Hussain MI, Bhuiyan MKI, Sumon SA, Hossain MI, Akhter A (2024) Enhancing Data Integrity and Traceability in Industry Cyber Physical Systems (ICPS) through Blockchain Technology: A Comprehensive Approach
4. Aljohani A (2023) Predictive Analytics and Machine Learning for Real-Time Supply Chain Risk Mitigation and Agility. Sustainability. doi: 10.3390/su152015088
5. Alonge E, Dudu O, Alao O (2024) The impact of digital transformation on financial reporting and accountability in emerging markets. 25–049. doi: 10.53771/ijstra.2024.7.2.0061
6. Atadoga A, Umoga UJ, Lottu OA, Sodiya EO (2024) Evaluating the impact of cloud computing on accounting firms: A review of efficiency, scalability, and data security. Global Journal of Engineering and Technology Advances 18:065–074. doi: 10.30574/gjeta.2024.18.2.0027
7. Attaran S, Attaran M, Celik B (2024) Digital Twins and Industrial Internet of Things: Uncovering operational intelligence in industry 4.0 ☆. Decision Analytics Journal 10:100398. doi: 10.1016/j.dajour.2024.100398
8. Chen Y (2020) IoT, cloud, big data and AI in interdisciplinary domains. Simulation Modelling Practice and Theory 102:102070. doi: 10.1016/j.simpat.2020.102070
9. Cramer C, John JD, Sender J (2022) Classification and Roundabout Production in High-value Agriculture: A Fresh Approach to Industrialization. Development and Change 53:495–524
10. Fatima Z, Tanveer MH, Waseemullah, Zardari S, Naz LF, Khadim H, Ahmed N, Tahir M (2022) Production Plant and Warehouse Automation with IoT and Industry 5.0. Applied Sciences 12:2053. doi: 10.3390/app12042053
11. Friederich J, Francis DP, Lazarova-Molnar S, Mohamed N (2022) A framework for data-driven digital twins of smart manufacturing systems. Computers in Industry 136:103586. doi: 10.1016/j.compind.2021.103586
12. Guo X, Zhang G, Zhang Y (2022) A Comprehensive Review of Blockchain Technology-Enabled Smart Manufacturing: A Framework, Challenges and Future Research Directions. Sensors 23:155. doi: 10.3390/s23010155
13. Gupta S, Verma JK (2023) Reverse Traceability Framework for Identifying Liability of Crashes for Self-Driving Vehicles Using Blockchains. Journal of Global Information Management (JGIM) 31:1–21. doi: 10.4018/JGIM.329961
14. Hader M, Tchoffa D, El Mhamedi A, Ghodous P, Dolgui A, Abouabdellah A (2022) Applying integrated Blockchain and Big Data technologies to improve supply chain traceability and information sharing in the textile sector. Journal of Industrial Information Integration 28:100345
15. Isbaih S, Noman HA, Aljarwan A, Owais IA, Yosry A, Bahroun Z (2024) Blockchain in Enterprise Resource Planning Systems: A Comprehensive Review of Emerging Trends, Challenges, and Future Perspectives. Management Systems in Production Engineering 32:571–586. doi: 10.2478/mspe-2024-0055
16. Islam R, Patamsetti V, Gadhi A, Gondu RM, Bandaru CM, Kesani SC, Abiona O (2023) The Future of Cloud Computing: Benefits and Challenges. International Journal of Communications, Network and System Sciences 16:53–65. doi: 10.4236/ijcns.2023.164004
17. Jamwal A, Agrawal R, Sharma M, Giallanza A (2021) Industry 4.0 Technologies for Manufacturing Sustainability: A Systematic Review and Future Research Directions. Applied Sciences 11:5725. doi: 10.3390/app11125725
18. Kamble S, Gunasekaran A, Mani V, Belhadi A, Sharma R (2022) Digital twin for sustainable manufacturing supply chains: Current trends, future perspectives, and an implementation framework. Technological Forecasting and Social Change 176:121448. doi: 10.1016/j.techfore.2021.121448
19. Khan Y, Su'ud MBM, Alam MM, Ahmad SF, Ahmad (Ayassrah) AYAB, Khan N (2022) Application of Internet of Things (IoT) in Sustainable Supply Chain Management. Sustainability 15:1–14
20. Khinvasara T, Ness S, Shankar A (2024) Leveraging AI for Enhanced Quality Assurance in Medical Device Manufacturing. Asian Journal of Research in Computer Science 17:13–35. doi: 10.9734/ajrcos/2024/v17i6454
21. Krzyżostan M, Wawrzyńczak A, Nowak I (2024) Use of Waste from the Food Industry and Applications of the Fermentation Process to Create Sustainable Cosmetic Products: A Review. Sustainability 16:1–33
22. Lin X, Chang S-C, Chou T-H, Chen S-C, Ruangkanjanases A (2021) Consumers' Intention to Adopt Blockchain Food Traceability Technology towards Organic Food Products. International Journal of Environmental Research and Public Health 18:912. doi: 10.3390/ijerph18030912
23. Liu J, Zhang H, Zhen L (2023) Blockchain technology in maritime supply chains: applications, architecture and challenges. International Journal of Production Research 61:3547–3563
24. Liu Z, Meyendorf N, Blasch E, Tsukada K, Liao M, Mrad N (2025) The Role of Data Fusion in Predictive Maintenance Using Digital Twins. pp 1–23
25. Madaki AS, Ahmad K, Singh D (2024) Information technology integration implementation in public sector organizations: Exploring challenges, opportunities, and future trends. Information Development 02666669241255661. doi: 10.1177/02666669241255661
26. Mourtzis D, Angelopoulos J, Panopoulos N (2022) A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0. Energies 15:1–29
27. Ngcobo K, Bhengu S, Mudau A, Thango B, Lerato M (2024) Enterprise Data Management: Types, Sources, and Real-Time Applications to Enhance Business Performance - A Systematic Review

28. Niu G (2025) Evaluation of Blockchain-Based Tracking and Tracing System With Uncertain Information: A Multi-Criteria Decision-Making Approach. IEEE Access 13:40795–40812. doi: 10.1109/ACCESS.2025.3546275
29. Oriekhoe OI, Oyeyemi OP, Bello BG, Omotoye GB, Daraojimba AI, Adefemi A, Oriekhoe OI, Oyeyemi OP, Bello BG, Omotoye GB, Daraojimba AI, Adefemi A (2024) Blockchain in supply chain management: A review of efficiency, transparency, and innovation. International Journal of Science and Research Archive 11:173–181. doi: 10.30574/ijsra.2024.11.1.0028
30. Pang J, Zhang N, Xiao Q, Qi F, Xue X (2021) A new intelligent and data-driven product quality control system of industrial valve manufacturing process in CPS. Computer Communications 175:25–34. doi: 10.1016/j.comcom.2021.04.022
31. Qian C, Liu X, Ripley C, Qian M, Liang F, Yu W (2022) Digital Twin—Cyber Replica of Physical Things: Architecture, Applications and Future Research Directions. Future Internet 14:64. doi: 10.3390/fi14020064
32. Rane N (2023) Integrating Leading-Edge Artificial Intelligence (AI), Internet of Things (IoT), and Big Data Technologies for Smart and Sustainable Architecture, Engineering and Construction (AEC) Industry: Challenges and Future Directions
33. Reshi I, Sholla S (2023) The blockchain conundrum: An in-depth examination of challenges, contributing technologies, and alternatives. Concurrency and Computation: Practice and Experience 36. doi: 10.1002/cpe.7987
34. Rojas L, Fritz AP, García J (2025) AI-Driven Predictive Maintenance in Mining: A Systematic Literature Review on Fault Detection, Digital Twins, and Intelligent Asset Management. Applied Sciences (Switzerland) 15:3337. doi: 10.3390/app15063337
35. Sanfiya S, Banu Ph.D. S (2025) Digital Twins & Industry 5.0 On Food Management. pp 87–105
36. Shrivastava A, Murali Krishna K, Lal Rinawa M, Soni M, Ramkumar G, Jaiswal S (2023) Inclusion of IoT, ML, and Blockchain Technologies in Next Generation Industry 4.0 Environment. Materials Today: Proceedings 80:3471–3475. doi: 10.1016/j.matpr.2021.07.273
37. Tavakol M, Dennick R (2011) Making sense of Cronbach's alpha. Int J Med Educ 2:53–55. doi: 10.5116/ijme.4dfb.8dfd
38. Ullah A, Younas M (2024) Development and Application of Digital Twin Control in Flexible Manufacturing Systems. Journal of Manufacturing and Materials Processing 8. doi: 10.3390/jmmp8050214
39. Vinay K, Goyal S, Nigam V, Jana M, Maitra A, Sharma H, Sahu KK (2024) A Confluence of Emerging Technologies Like IoT, Edge & Cloud Computing, Blockchain, Industry 4.0 & 5.0, AI & ML toward the Realization of Eco-Friendly Supercapacitors. American Chemical Society (ACS), pp 163–204
40. Zhu P, Hu J, Li X, Zhu Q (2023) Using Blockchain Technology to Enhance the Traceability of Original Achievements. IEEE Transactions on Engineering Management 70:1693–1707. doi: 10.1109/TEM.2021.3066090

Biography

Samar Gupta is a PhD scholar at the Indian Institute of Foreign Trade in Delhi, India. He is Sr. Vice President and Group Chief IT Officer for Minda Corporation at Noida, Uttar Pradesh, India. He is Ex-Microsoft, Ex-Wipro, Ex-Stryker and Ex-Flex. He holds an MBA from Management Development Institute, India and attended a Harvard leadership program, an MS in Engineering from Oklahoma State University (USA), and a BE in Electronics and Telecommunications from Nagpur University (India). He is responsible for managing Digital Transformation and Information Technology across the Minda Corporation. The Group is comprised of 35 automotive parts manufacturing plants across India, Vietnam and Indonesia. His research interests are on how Information Technologies can improve the overall circular supply chain and traceability in the automotive sector.

Dr. Jitendra Kumar Verma is an Assistant Professor of IT & Knowledge Management Discipline at Indian Institute of Foreign Trade (Kakinada Campus) of Andhra Pradesh State of India. He received his M.Tech and PhD in Computer Science from Jawaharlal Nehru University, New Delhi, in 2013 and 2017, respectively. He obtained his degree of B.Tech in Computer Science & Engineering from Kamla Nehru Institute of Technology (KNIT), Sultanpur, in 2008. Over his short career, he has published numerous papers in peer-reviewed international journals and books with renowned publishers, conference proceedings papers, and book chapters. He has organized several international conferences, seminars, and workshops. He delivered numerous invited talks and seminars at various platforms of national and international repute. He authored one book, Green Cloud Computing (Lambert Academic Publishing, 2016), and edited five books, Applications of Machine Learning (Springer Verlag, 2020), Computational Intelligence and Its Applications in Healthcare (Elsevier Academic Press, 2020), IoT and Cloud Computing for Societal Good (Springer International Publisher, 2021), and Advances in Augmented Reality and Virtual Reality (Springer Verlag, 2022), Cloud IoT: Concepts, Paradigms and Applications (Chapman and Hall/CRC — Taylor & Francis Group). He is an awardee of the prestigious DAAD "A New Passage to India" Fellowship (2015–2016) funded by the Federal Ministry of Education and Research – BMBF, Germany, and German Academic Exchange Service. He worked at Julius-Maximilian University of Würzburg, Germany as a visiting research scholar during 2015-16. He has organized several international conferences, seminars, and workshops and delivered several invited talks. He is associate editor and guest editor of several international journals. He is also a member of several national and international societies/professional bodies, including ACM (USA), IEEE Industrial Applications Society (USA), IEEE Young Professional (USA), IEEE (USA), Institut De Diplomatie Publique (United Kingdom), Hyderabad Deccan ACM Chapter, Computer Society of India (New Delhi), and Soft Computing Research Society (New Delhi). Recently, He is elected as Senior Member of IEEE (USA) by high panel of academicians worldwide. He serves as a reviewer for various high-impact international journals, conferences, and workshops. His core research interests include Software engineering, Cloud Computing, Edge Computing, Blockchains, Internet of Things, Social computing, Image Processing, Artificial Intelligence & Machine Learning, and Soft Computing Techniques.