Internet of Things in Industry 4.0: Applications, Challenges and Opportunities

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Abstract
With the integration of IoT into modern industry, operations have been redefined, enabling real-time data exchange, predictive maintenance, automation, and smart decision-making. Finally, this paper conducts a systematic literature review of 30 scholarly articles published from 2020 to 2025 to examine the applications, challenges, and advancements of IoT in the industrial environment. And they explore various areas, including security, scalability, interoperability, and supply chain optimization. To reaffirm a gap that already exists, the research offers an Integrated IoT Security and Efficiency Framework that is AI-driven threat detection backed by blockchain-based security, edge computing, and an adaptive supply chain. The study also proposes a structured taxonomy and a flowchart for the most common problems and their mitigation solutions. Security standards, protocol standardization, and robust security measures are a concern, while IoT has the potential to increase operational efficiency and sustainability. This research offers practical guidance to industry sectors seeking to run secure, scalable, and intelligent IoT in the context of an ever-changing Industry 4.0.
Keywords:
IoT, Industry 4.0, Smart Manufacturing, Predictive Maintenance, Cybersecurity, Edge Computing, Supply Chain Optimization.

1. Introduction

Industry 4.0 marks another paradigm shift in industrial operations, where digital technologies, including the Internet of Things (IoT), Artificial Intelligence (AI), Big Data analytics, Robotics, and Cloud Computing, are converging [1]. Coupled with profound data acquisition and processing automation, and intelligent decision-making. Industry 4.0 effectively changes the course of manufacturing across borders, enabling interconnected, self-optimizing manufacturing environments [1]. The real strength of this transformation lies in IoT, an anchor of smart manufacturing that enables seamless communication among machines, systems, and people, making manufacturing more efficient, agile, and productive.

For instance, in Industry 4.0, IoT is about a network of sensors, actuators, and smart controllers that collect, transmit, and analyze real-time data. Embedded devices are used in industrial equipment, production lines, and supply chains, enabling manufacturers to monitor machine health, track inventory, and optimize flows online [2]. Through IoT-based predictive maintenance, industries can forecast equipment failures before they occur, reducing unplanned downtime and minimizing plant operational disruption. Furthermore, real-time monitoring of production parameters ensures quality control, thereby reducing defects and improving product consistency [3]. These advancements not only improve overall operational efficiency but are also sustainable, as they help reduce waste and increase energy efficiency.

Finally, the incorporation of IoT into Industry 4.0 also enables supply chain management by extending visibility across production and distribution processes from end to end. IoT-enabled tracking systems and smart logistics can also be used by manufacturers to manage inventory, shorten the lead time and improve demand forecasting [4]. Any supply chain created is an additive function of suppliers, distributors, and indeed manufacturers, integrating

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with each other to build a more agile and responsive supply chain. IoT-based automation also helps them with mass customization, enabling industries to meet consumer requirements in specific ways without losing efficiency or cost-effectiveness.

Although IoT has the potential to change, adoption in Industry 4.0 is marred with challenges. Despite the general improvement in the situation, security vulnerabilities and cyber threats persist, particularly as industrial devices in critical infrastructure become increasingly connected, increasing the risk of cyber-attacks and information leaks [5]. To safeguard sensitive industrial data, it is paramount to implement robust cybersecurity measures, including encryption, access controls, and threat detection mechanisms. Furthermore, interoperability issues arising from connecting different IoT devices and proprietary systems limit seamless connectivity. Enhancing device compatibility and data exchange requires standardizing and developing universal communication protocols [5]. Moreover, the deployment of IoT infrastructure requires significant investment in technology, skilled workforce, and system upgrades, which, in turn, limits the financial capacity of SMEs [6].

This study investigates the use of IoT in Industry 4.0, discusses its advantages and challenges, and outlines best practices for effective implementation. This study examines industrial transformation enabled by IoT in real-world use cases, drawing on a thorough review of existing research to understand how it can improve efficiency, productivity, and sustainability. The paper discusses how AI, edge computing, and digital twin technology are emerging as enablers of the capabilities IoT provides in Industry 4.0. By assessing core concerns, including cybersecurity, scalability, and regulatory compliance, this paper sets out a path for industries to leverage the full potential of IoT in the smart manufacturing and digital transformation era.

This paper is organized as follows: Section 2 contains the literature review of related work, and Section 3 outlines the Method & Methodology adopted to conduct the research. Section 4 provides results and discussion, and a conclusion is offered in Section 5.

2. Materials and Methods

This research follows the Systematic Literature Review (SLR) methodology and adheres to PRISMA to take a structured, methodical approach to current studies of IoT in Industry 4.0. To improve transparency (reproducibility) and minimize bias in the process, the PRISMA framework was chosen (only high-quality or relevant studies were included in the analysis).

This study consists of a meticulous process of searching, screening, and synthesis of the research papers, conference proceedings, and industrial reports (RP) covering the use of IoT in Industry 4.0 and their roles in areas, for example, predictive maintenance, real-time monitoring, industrial automation, security challenges, and supply chain optimization.

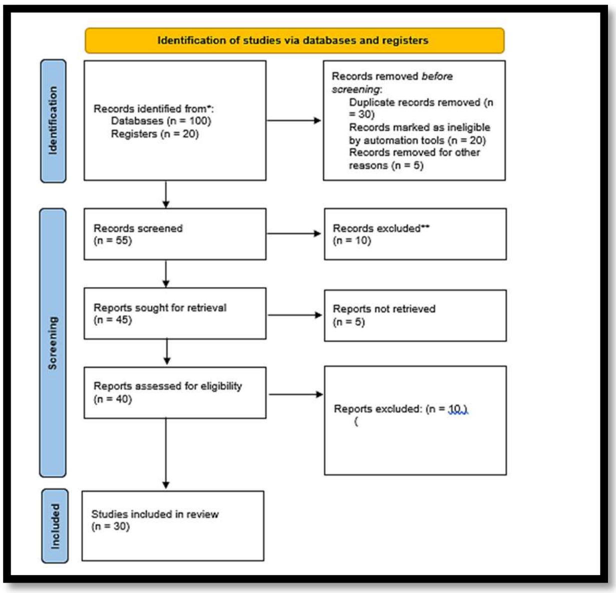

Figure 1. PRISMA Model

According to the study, the literature covered spans from 2020 to 2025 to provide both historical background and the most recent advances in the utilization of IoT in Industry 4.0. This research explores two primary sources of data: well-established leading digital libraries and databases such as Google Scholar, IEEE Xplore, ScienceDirect, SpringerLink, and ACM Digital Library.

These repositories contain peer-reviewed articles, system views, technical reports and case studies concerning the adoption of IoT in industrial automation. To that end, selected white papers and industry reports from three reputed bodies, the Industrial Internet Consortium (IIC) and the World Economic Forum (WEF), were also considered to look at real-world implementations and new trends.

2.1. Search Strategy

For the extraction of relevant research papers, a set of keywords and Boolean operators were employed. The following is the list of the search queries included in the process.

- ("Internet of Things" OR "IoT") AND ("Industry 4.0" OR "Smart Manufacturing")
- ("IoT applications" AND "Industrial Automation")
- ("IoT-enabled Predictive Maintenance" OR "Industrial IoT Security Challenges")
- ("IoT Sensors" AND "Real-time Data Analytics" AND "Manufacturing")

Inclusion and Exclusion Criteria:

- Inclusion criteria to refine the search results are as mentioned below.
- Studies of IoT integration in industrial settings of Industry 4.0.
- Empirical, case study and other evidence-based research articles.
- It ensures that the papers have been published between 2020 and 2025 to keep them up to date.
- The exclusion criteria eliminated:
- Studies that focused solely on consumer IoT applications.
- Articles without technical depth or those lacking empirical data.
- Duplicate studies from multiple sources.

Data Extraction and Analysis:

The selected studies were systematically classified with respect to key aspects of understanding the role of IoT in Industry 4.0, including industrial applications, IoT architecture, security challenges, and economic impact. The aims of identified trends, technological advancements, and critical implementation challenges across different industrial domains were determined through structured thematic analysis to provide helpful direction for platform engineering. This thematic categorization enabled a thorough evaluation of the interplay among components of IoT deployment, thereby enabling a nuanced understanding of its merits and shortcomings. The IoT architecture was reviewed by studying various frameworks, network protocols, and connectivity standards in the industrial arena. It reviews the studies discussed in relation to edge computing, cloud-based IoT solutions, and how artificial intelligence (AI) and machine learning (ML) generally improve industrial automation. Moreover, the potential application of IoT in the industrial sector was examined by introducing how sectors such as manufacturing, logistics, and supply chain management are utilizing IoT-based solutions to improve operational efficiency, enable predictive maintenance, and deploy intelligent monitoring systems. The case studies demonstrating real-world implementations were beneficial for understanding the practical challenges and benefits of IoT integration. The heightened risk of cyber threats in highly connected industrial environments was considered for the critical analysis of security challenges with IoT deployment. These studies were used to evaluate insights into security frameworks, data encryption, and authentication protocols to overcome cybersecurity risks. In addition, data privacy, network vulnerabilities, and compliance with regulatory standards were discussed to holistically explain the security threats in industrial IoT (IoT) applications. The studies focused on the need for robust security systems, such as intrusion detection systems and blockchain-based security models, to safeguard industrial operations from cyberattacks.

Cost-benefit and security dynamics of the positioning of IoT into Industry 4.0 are at the core of impact analysis. Insights from the reviewed literature have focused on the investment needed in a financial sense for IoT adoption, operational cost savings, return on investment (ROI) metrics, and security issues. To understand how patterns of adoption rates, efficiency improvements, cost reductions, and security concerns are affected by IoT in industrial automation, a proper analysis was conducted. The studies also identified the factors essential to the scalability of IoT solutions, including infrastructure costs, technological readiness, and workforce training. While the literature review has a common theme, it should be synthesized into an integrated framework outlining how IoT practices can be applied in Industry 4.0. This framework will cover key matters such as cybersecurity, interoperability, scalability, and regulatory compliance. This study aims to offer a structured set of advice for overcoming challenges and achieving maximum IoT benefits for industries interested in exploiting IoT technologies to increase operational efficiency, resilience, and competitive advantage in the digital environment.

3. Results

In [1], the authors critically explore IoT's applications across different fields and its prospects. The fields of agriculture, healthcare, smart cities, and Industry 4.0 have flourished through the transformative role of IoT, which enables greater efficiency, data-driven decision-making, and automation. The contribution of IoT in the fields mentioned above can be explored through the upgradation of urban infrastructure, patient care, advanced farming operations, and advanced manufacturing. The future of the IoT application is promising, with the incessant growth of artificial intelligence and machine learning that can address existing shortcomings, such as affordability and security challenges.

The authors in study [2] highlighted the emergence of rapid automation due to the impact of COVID-19, which necessitated a high-quality automation system to monitor IoT data. Industry 4.0 is advancing network technology that requires an effective architect to deliver real-time solutions in the remote working environment. The paper presents an IoT-SDN model that leverages multiple controller instances to build a robust, automated system while reducing security risks. The article is significant for enhancing knowledge of the core driving force behind IoT and for providing a networking system to mitigate its limitations.

The article [3] further highlights the knowledge gaps regarding the IoT application in Industry 4.0. The manufacturing sector has benefited from IoT, which enables connections between the digital and physical worlds to advance customer service, improve productivity, enable real-time communication, enhance inventory management, and more. However, concerns about privacy and data security arise from a lack of global coherence. Thus, the future of Industry 4.0 lies in adopting IoT with improved modelling to achieve its best outcomes, such as asset utilization, productivity, reduced downtime, operational efficiency, consumer engagement, resilience, and sustainability.

Similarly, [4] provides a detailed understanding of the application of IoT in Industry 4.0.

However, the authors emphasized several factors beyond productivity and operational efficiency that are significant for understanding the massive impact of IoT applications. The authors acknowledge the role of IoT in transforming traditional factories into advanced factories by preventing machine failure or reducing downtime. However, IoT has significant implications for energy conservation and supply chain management that are crucial for better environmental outcomes and workplace safety. Thus, the profitability associated with IoT is not only vital to organizational benefit but also for shaping broader social and community perspectives.

On the other hand, [5] presents a framework for an integrated IoT system to help industries maximize their benefits. The authors describe IoT as a complex network composed of various interconnected devices that sense, track, and process. The presentation of the three-phase architecture of IoT, including the Collection phase that optimizes understanding of the physical world through RFID, GPS, or NFC; the Transmission phase that transfers data to various external points through gateways; and the utilization phase that conducts semantic analysis. The last phase integrates the service platform layer, such as P2P and SOA.

Another study [6] provides insights into the historical transformation, status, and future opportunities for Industry 4.0 to leverage the IoT. The authors reviewed 891 papers published from 2014 to 2020 on IoT in Industry 4.0. The study's findings suggest that the IoT was introduced in 1999 by Kevin Ashton and has continued to evolve, aiming to connect global infrastructure through technological devices. The IoT was revolutionized in 2018 with the integration of distributed systems, big data analysis, and cloud computing, which has driven demand for Industry 4.0's advanced, data-driven solutions to business challenges.

In [7], the authors conducted a systematic literature review to evaluate research gaps across various aspects of Industry 4.0, including the limitations and challenges of utilizing IoT or wireless sensor networks (WSN). The authors highlight various security attacks, such as Denial-of-Service, Replay, and Black Hole attacks, that pose significant challenges to maximize the benefits of IoT in building a holistic network system. The study's findings provide a detailed analysis of Network Security attacks in WSN and IoT, which will help future researchers formulate solutions to secure Industry 4.0. On the other hand, [8] discussed the need for digital twins to complete the industry 4.0 perspective. Digital twins are software models of real-world objects that provide a digital identity for those objects. The system leverages data analytics, AI, and IoT to improve its ability to detect duplicate items via sensors. Thus, the physical components of IoT devices can be duplicated through a digital twin to capture real-time data. The article is significant for enhancing knowledge of the implications of IoT for developing other software models that enrich the fourth industrial revolution.

In [9], the authors discussed the strengths of Industry 4.0, which optimizes the flexible manufacturing system (FMS) through communication and sensor technologies that can be integrated with a broader networking system. The high-tech devices can serve a consumer-focused strategy to develop customized products. There are a few limitations to Industry 4.0 due to cross-functional endeavors involving different stakeholders. However, the limitations can be mitigated by utilizing future scope to incorporate automation and other virtualized technologies. Thus, the implementation of IoT is one of those technologies that limit human intervention by enabling a more powerful system of automation.

Another article [10] discussed the influence of the fourth industrial revolution on medical or healthcare services. The cyber-physical systems enabled by Industry 4.0 have revolutionized the healthcare sector through technologies such as big data analysis, AI, and IoT. The revolution in the healthcare system includes a cloud-based recording system, rapid quality measurement, and remote monitoring via IoT. Thus, digitization has not only benefited the manufacturing industry but also enabled the development of a healthcare system that integrates automation and data-driven solutions.

In [11], the authors aim to explore the use of IoT across different industrial sectors to improve operational productivity and enable real-time solutions. However, the authors also noted that the transformation towards Industry 5.0 might be achieved through an effective balance between human strength and digital technology. The application of IoT to effectively manage warehouses is crucial for resource management. Moreover, IoT has widespread applications in supply chain management, as well as in monitoring and control systems. The robust security of all physical devices is a significant concern for the utilization of IoT. Therefore, further research is required to develop effective methods to protect against the threats posed by IoT.

Similarly, [12] highlights concern about security breaches and presents a secure wireless mechanism to maintain data security transparency. The proposed framework focuses on probability, authentication, and openness by incorporating a blockchain networking system, which is significant for real-time tracking across a vast network. The authors suggest registering all sensors that monitor product or worker locations on the blockchain network. The activity of each sensor will be recorded by the blockchain devices. Therefore, the inclusion of blockchain technology in IoT can enhance the transparency and authentication for product shipment and other activities.

In [13], the requirements of cyber-physical systems (CPS) for empowering Industry 4.0 were discussed by exploring their applications. Industry 4.0 offers a unique manufacturing process that connects all units through technological tools. The CPS provides an integrated system by combining different sensory devices to deliver real-time information access and reduce machine downtime. The innovative manufacturing process in Industry 4.0 is enabled by different networking systems, such as IoT. Thus, the paper reveals the CPS's detailed role in increasing the production capacity of various industries.

The article [14] supports the view that IoT and CPS are significant pillars for enabling smart manufacturing in Industry 4.0. The concepts of innovative production, intelligence production, and predictive maintenance (PdM) are implemented through machine learning (ML), IoT, and big data. The authors investigate data failure by measuring the Remaining Useful Lifetime (RUL) of different components. The paper is thus significant for enhancing knowledge of data failure challenges and for providing a novel approach for ML prediction models to evaluate the best composition for interpretability, predictive performance, and computational efficiency.

Another study [15] analyses the requirements for product traceability for electronic manufacturing service companies (EMS). The paper investigates various IoT technologies to compare the positive and negative outcomes of product traceability. Finally, a comparison between RFID and SigFox has been presented through a critical analysis of their predictability, traceability, and suitability. The study suggests that Sigfox is the most suitable technology for EMS services. Connectivity, price, bandwidth, and Position tracking are all efficient to optimize for better outcomes while minimizing the effort required to improve traceability.

In [16], the development process of Industry 4.0 has been discussed to investigate its applicability in the apparel or textile industry. The study's findings reveal that the textile industry has sufficient demand for a consumer-centric approach that can be initiated through the application of big data, IoT, and augmented reality. Moreover, the social implications of Industry 4.0 are particularly relevant to the textile industry, given its high waste production and significant energy consumption. However, the requirements for automation and computerization are at a nascent stage and can be improved by looking to countries that have successfully transformed their textile industries.

In [17], the relevance of Industry 4.0 has been evaluated in the context of sustainable supply chain management (SCM). It is interpreted that the demand to reduce environmental footprint has become a significant concern for all industries, which are required to adopt a circular economic system to optimize suitable SCM. The findings highlight the benefits of Industry 4.0 in managing the circular economy through the ReSOLVE model, which helps regenerate, loop, exchange, optimize, and share to improve sustainable performance through advanced technological solutions.

On the other hand, [18] aims to explore platform services in the context of Industry 4.0. The two primary platform services that have been focused on herein are the service platform and product-selling platform. The operational issues highlighted here include decision support, information use, consumer behavior, and the manufacturing process. The study's findings show that the implementation of advanced technologies enabled by Industry 4.0 has significant implications for improving platform services. The results indicate a framework of "3As": the platform service can "adopt" technology that aids in "addressing" operational issues to "achieve" positive outcomes.

Another study [19] explores the utilization of IoT to advance the agricultural sector. The authors highlight that precision agriculture, along with smart greenhouses, has been enabled by IoT infrastructure and technological services such as actuators, radio-frequency devices, satellites, and aerial vehicles. The implementation of IoT in agriculture creates a sustainable framework for mitigating ecological degradation, improving production, conserving the environment, and managing energy waste. However, the challenges have been highlighted in the context of optimal resource management, given the uneven distribution of technological tools and their greater concentration in high-income countries.

In [20], the confluence of all major technologies has been used to build a single model factory to understand the effects of Industry 4.0 on advancing the manufacturing process. The research highlights that Industry 4.0 can be conceptualized as relying on cyber-physical systems that enable autonomous, advanced communication and the decentralization of decision-making to foster productivity. The study also considers IoT as one of the seven technological pillars of the fourth industrial revolution. IoT is a multifaceted network system that empowers industrial efficiency through linking the physical and digital worlds.

Another study [21] explores the transformation of the healthcare system, smart cities, and farming through the adoption of IoT, which enables data-driven decision-making and integrates physical objects. Healthcare has been transformed by the application of modern IoT systems, which are critical for allowing real-time data analysis, individualized treatment plans, remote monitoring, and more. The automation system enables crop monitoring and advanced irrigation, reducing operational costs and improving productivity. The sensory system and automation help to reduce congestion and resource allocation. Thus, the article provides a holistic view of IoT implementation.

In [22], the implications of IoT for SCM and logistics were evaluated through a bibliometric analysis. The analysis reveals that the advanced technology of IoT, such as RFID, transforms the function of traditional logistics into a system of supply with proper monitoring and traceability. The paper also seeks to understand the challenges of traceability and the security objectives for utilizing the advanced process. The results highlight that the use of blockchain technologies can improve resource management by properly evaluating the tractability of different points in the supply system. Thus, the article enhances the field for future research to optimize the more advanced implications of IoT.

Again, in [23], the concept of digital twins has been elaborated in the realms of Industry 4.0. The relationship among IoT, Industry 4.0, and the digital twin is significant, as IoT expands the pathways for the digital twin to efficiently connect the physical and digital worlds. The advanced system facilitates critical decision-making, detailed simulations, and performs analytics. The inner potential has been conceptualized through a "3D digital twin," rather than a digital twin, to demonstrate the applicability of the systems across diverse areas such as industry, energy, agriculture, and healthcare.

In [24], the authors evaluate the holistic Industry 4.0 paradigm that integrates IoT and AI-driven optimization. The advancement of industrial processes through increased efficiency is a core construction of Industry 4.0. The paradigm integrates different technological tools to create a synergy of modern solutions for rapid productivity and customization. The broader aspects of Industry 4.0 are thus optimized through systematic collaboration among advanced technologies. Therefore, it is crucial to strategically use all the components to reduce costs and achieve higher benefits.

The research [25] explores the application of IoT in the electronic commerce (e-commerce) sector, which is a new trend in the industry. The fusion of digital and physical territories is the core of IoT, enabling high-end product manufacturers to optimize operations and achieve rapid productivity gains. The advent of e-commerce also justifies the transition of IoT, as the sector is highly dependent on customization to cater to a wide range of consumers. The findings of the study show that the concept of vertical IoT is constructed of three different layers, such as fog, edge, and cloud, which can be optimized by the e-commerce sectors.

In [26], the authors seek to investigate the utilization of digital twins (DT) in the context of Building Information Modelling (BIM). BIM is adopted to accelerate construction processes by leveraging cloud computing, big data, IoT, and related technologies. The study's findings highlight that applying DT can enhance BIM's capacity to improve the built environment. However, there are significant challenges in optimizing the DT due to a lack of real-world experiments. Thus, there is ample scope for research to evaluate the built environment by taking cues from other industries.

The research [27] presents an insightful exploration of the application of IoT to connect physical objects through digital technologies. The primary function of IoT is to integrate sensor networks. The functioning of IoT benefited inventory management by tracking the supply system through data-driven solutions and advanced monitoring. Moreover, the implementation of IoT enables industries to enhance waste management and cost savings. The field of agriculture is also advancing through remote monitoring and automated irrigation systems. However, the utility of IoT in the agricultural sector can be enhanced by increasing farmers' knowledge of its use.

In [28], a critical analysis has been presented to evaluate the impact of Industry 4.0 on the bakery sector. The bakery sector has been transformed through the application of the technological tools offered by the fourth industrial revolution. Wireless sensor networks, blockchain, robotics, and other automation systems have significantly met the requirements for managing supply chains, reducing waste, improving order management, and addressing different areas. One of the key focus areas for the bakery industry is engaging with consumers; thus, a data-driven approach enables the sector to deliver personalized experiences.

Another study [29] discusses the challenges of optimizing IoT benefits, including poor connectivity in remote locations. The research also highlights significant solutions to the challenges, such as emphasizing the need for connectivity between satellite and terrestrial networks. Thus, the article offers a more advanced, elusive approach to leveraging the full benefits of IoT. The findings suggest that communication through low Earth orbit satellites is a significant means of reducing the challenges of remote networking. Furthermore, it shows that IoT coverage can be increased through a low-power wide-area network (LPWAN).

In [30], an analysis of convergence between IoT and big data analysis was conducted using Natural Language Processing. The outcomes of the research suggest that the continuous data flow from various applications, such as social media, enhances the potential to collect real-time data, enabling different industries to utilize advanced management systems for energy, costs, and sales. The convergence of the two network systems creates a more elusive path for predictive maintenance in the context of intelligent traffic systems, manufacturing, and the use of personalized solutions in sectors such as healthcare or baking. Thus, a significant focus on transparency and security can empower a broader range of management through the application of IoT.

Table 1 provides a summary of reviewed literature on IoT applications in Industry 4.0, encompassing more than a decade.

Table 1: Summary of literature review

No.	Year	Study Objective	Tools/Frameworks	Key Findings	Future Directions
[1]	2023	The authors investigated IoT application in different fields and perspectives.	IoT, AI, Big Data Analytics	As compared to the past, IoT has made healthcare, agriculture, smart cities, and Industry 4.0 more automated and have helped improve decision making in those fields.	Integration of AI and ML can be made to handle security and affordability issues.
[2]	2022	Performs analysis of impact of IoT and SDN framework on remote monitoring and automation in the industry 4.0 context.	SDN-IoT Model	The IoT- SDN model improves the automation and the security of the industry 4.0 applications.	Mitigating cybersecurity risks for the IoT architectures.
[3]	2021	Role of IoT was reviewed by the authors is domains of in manufacturing, productivity, and communication.	IoT Sensors, Edge Computing	IoT has the capability to bring about enhancement in aspects such as productivity, real-time communication and others such as inventory management.	Improving IoT modeling
[4]	2023	The authors examined the role that IoT plays in transforming traditional factories	IoT Networks, Predictive Maintenance	Using IoT machine failures can be prevented thereby bringing in reductions in downtime. This in turn improves supply chain management.	Advanced IoT integration
[5]	2021	Proposed an integrated IoT system architecture for industrial application.	RFID, GPS, NFC	IoT networks enhance production monitoring and tracking system.	To increase interoperability and standardize IoT frameworks.
[6]	2022	It reviewed historical transformation and future opportunities of IoT in Industry 4.0.	Cloud Computing, Distributed Systems	IoT opens new business solutions and the digital transformation path.	Research in keeping IoT integrated with distributed AI systems.
[7]	2023	IoT security risks of Industry 4.0 were investigated.	Blockchain, AI-based Security Models	The IoT is limited by security vulnerabilities such as DoS and replay attacks.	Creating standardized security protocols for the industrial IoT networks.
[8]	2023	Digital twin technology applied to integrate with IoT in Industry 4.0.	AI, Data Analytics, Digital Twin	Digital twins enable both real time analysis of data as well as a level of automation.	To bring about enhancement in AI driven analytics for predictive maintenance.

[9]	2022	It has explored a variety of flexible manufacturing systems (FMS) enabled by Industry 4.0.	IoT, Sensor Technologies	IoT, the Application of Sensor Technologies combines customization and the consumer focus to leverage IoT-driven FMS.	Incorporating automation processes to minimize the use of humans in the iteration.
[10]	2021	Investigated the role of the different Industry 4.0 domains on healthcare.	Cloud-based IoT, AI	Remote monitoring and automation are the biggest revolution brought by IoT for the healthcare industry.	Improving the security of healthcare data by enhancing them into real time analysis.
[11]	2023	Analyzed IoT applications in warehouse automation and Industry 5.0.	IoT Sensors, Automated Warehousing	IoT makes warehouse more efficient and improves the operations of the store or supply chain.	Towards models of human technology interaction for Industry 5.0.
[12]	2022	A framework for secure IoT communication was proposed based on a blockchain.	Blockchain, IoT Security Protocols	Blockchain facilitates transparency, authentication and traceability.	Blockchain for end to end industrial IoT security implementation.
[13]	2023	It explored cyber-physical systems (CPS) in Industry 4.0.	IoT, CPS Frameworks	CPS is frameworks of smart manufacturing and real time monitoring.	This was done to optimize CPS for predictive maintenance and automation.
[14]	2023	Reviewed how IoT may be implemented in support of smart manufacturing via the PdM (predictive maintenance).	Machine Learning, IoT, Big Data	Equipped with predictive maintenance, downtime is reduced and the equipment longevity is improved	Achieving predictive analytics through AI based IoT solutions.
[15]	2021	Examined IoT based traceability solutions for manufacturing electronics.	RFID, SigFox	Sigfox technology assists products in gaining traceability and supply chain visibility.	Comparative studies can be conducted to realize all alternative IoT technologies that are there for traceability.
[16]	2022	The impact of Industry 4.0 on textile sector was investigated.	Big Data, IoT, Augmented Reality	This technology of IoT facilitates textile production based on consumer and waste reduction.	Automating and digitalizing the textiles.
[17]	2023	Evaluated Industry 4.0 for the sustainable supply chain management (SCM).	Circular Economy, IoT	In circular economy, IoT can help to accomplish optimal resource building through IoT enabled SCM.	Using real time IoT based decision making to enhance SCM sustainability.
[18]	2022	It explored the platform services and operational challenges for Industry 4.0.	IoT, AI-based Decision Support	Adaptive decision-making models improve the platform services with the help of IoT.	Developing AI-integrated frameworks for platform optimization.
[19]	2023	Explored IoT applications in smart agriculture.	IoT, Actuators, Remote Monitoring	IoT enables precision farming, environmental conservation, and energy management.	Exploring ways of developing AI integrated frameworks for

					platform optimization.
[20]	2024	Conducted analysis of Industry 4.0 in model factories.	Cyber-Physical Systems, IoT, Automation	Industry 4.0 is the integration of digital and physical environments to enhance productivity by automating the process for digitalization.	Practice of expanding IoT integration for decentralized decision making in factories is needed.
[21]	2023	It reviewed IoT's transformation of healthcare, smart cities and farming industries.	IoT, AI, Data-Driven Decision Systems	IoT helps in improving resource allocation, congestion management, and automation of healthcare.	Expanding the scope of the AI based automation for the urban infrastructure as well as the healthcare.
[22]	2024	It has evaluated IoT in supply chain management and logistics.	RFID, Blockchain, IoT Sensors	This contributes to providing better traceability, resource optimization and security for logistics.	Improving the adoption of IoT based on transparency achieved with the help of blockchain.
[23]	2023	Digital twin technology in this investigated industrial 4.0.	Digital Twin, IoT, AI	Digital twins make predictive maintenance as well as industrial processes more efficient.	Better real time analytics with the development of 3D digital twins.
[24]	2024	IoT and AI based optimization for Industry 4.0 was explored.	IoT, AI, Big Data	AI powered IoT brings about improved industrial process automation and greater cost savings.	Deep learning model's integration to enhance the efficiency of the IoT.
[25]	2024	Studies were done on analyzed IoT applications in e commerce and online retail.	Vertical IoT, Edge Computing, Cloud Computing	IoT provides the opportunity to make personalized shopping and the automation of supply chain possible.	Applying IoT in smart retail and logistics models.
[26]	2024	It reviewed IoT and Digital twin in the Building Information Modeling (BIM).	IoT, Cloud Computing, BIM	BIM and IoT together help improve BIM's efficiency and in real time monitoring in construction.	How to apply digital twins in architecture in real world.
[27]	2025	It focused on examining a role that IoT has played in the physical-digital integration in inventory management.	IoT, Sensor Networks	IoT reduces inventory spots, decreases waste, and helps to save money.	With real inventory analytics powered by AI to be able to have real time insights.
[28]	2025	The impact of Industry 4.0 on the bakery sector was investigated.	IoT, Blockchain, Robotics	IoT helps in the reduction of waste in the supply chain, order management.	To create personalized IoT based experience that will increase the engagement of the consumers.
[29]	2025	Challenges in developed connectivity in remote IoT applications.	Satellite Networks, LPWAN	Remote areas have been improved for IoT connecting through low Earth orbit satellites.	Investigation of hybrid IoT communication

					networks for global communications.
[30]	2025	Investigated the possibility of IoT and big data analytics integration.	IoT, NLP, Data Flow Analysis	Both IoT and the big data integration are used for predictive maintenance and energy management.	Developing big data analytics

3. Proposed Mechanism to Address Gaps in IoT Implementation

This paper reviews the existing literature and proposes an Integrated IoT Security and Efficiency Framework to address major gaps in IoT adoption within Industry 4.0. Specifically, this framework is motivated by key challenges identified in literature, such as security ([7], [12]), scalability ([19]), and interoperability ([22], [24]).

3.1 Key Components of the Proposed Framework

AI-Enhanced Cybersecurity Protocols: This has increased cybersecurity threats in Industry 4.0 IoT networks, including data breaches, ransomware, and DDoS attacks. Often, detecting and mitigating sophisticated cyber threats has proved inadequate with traditional security measures, such as firewalls and password authentication. AI-driven cybersecurity protocols use ML or DL algorithms, enabling AI to enhance its threat detection and prevention capabilities. These systems are AI-based, analysing network traffic, identifying anomalous patterns, and alerting to cyber threats in real time. In addition, AI-based security solutions help implement automated incident response, reducing human intervention and response time to security breaches [31-35].

Edge Computing for Scalability: Real-time data generated by IoT devices requires efficient processing and transmission mechanisms. When we rely solely on cloud-based architecture, we will experience latency issues and can't use industrial IoT apps effectively.
Decentralized data processing is the term for what edge computing does: localizing data processing to systems at the edge, far from centralized cloud servers. It reduces the latency, reduces dependence on internet connectivity and makes the overall industrial IoT system more scalable [36-40].

Standardized Communication Protocols: The biggest challenge to industrial IoT adoption has been the lack of common protocols in IoT (which has caused incompatibility between various IoT devices and platforms). Because a unified standard doesn't exist, there is often a fragmented IoT ecosystem that makes it difficult to unify devices from different vendors. To eliminate this, the proposed framework focuses on creating standardized communication protocols that facilitate interoperability among devices across industries. Well-defined protocols such as MQTT (Message Queuing Telemetry Transport), CoAP (Constrained Application Protocol), and OPC UA (Open Platform Communications Unified Architecture) provide secure, efficient communication between machines (M2M) [41-45].

Blockchain-Based Security Solutions: As a decentralized method for securing industrial IoT networks, blockchain technology provides immutable, tamper-proof data records and improves authentication mechanisms. Traditional centralized security models are vulnerable to single points of failure, so security can be compromised easily in a big way through spamming or by someone just begging them. By decentralizing data storage and authentication processes, data integrity and transparency are achieved, enabled by blockchain's distributed ledger architecture and helping address these risks. Blockchain can be used for secure device authentication, encrypted data exchange and supply chain transparency in the industrial IoT applications [46-50].

IoT-Powered Smart Maintenance Systems: Unplanned equipment failures can cause significant financial losses in industrial operations. However, these traditional methods of maintenance, reactive maintenance (preparing equipment based on its failure) and scheduled preventive maintenance (performing routine checks at fixed intervals) are usually inefficient and expensive. Ultimately, integrating an IoT-powered predictive maintenance system addresses these challenges by continuously monitoring equipment performance and predicting upcoming failures. Currently, IoT-enabled smart maintenance systems use advanced sensors like grey hammer, advanced machine learning models, and cloud-based analytics to collect and analyze real-time operational data from industrial machinery [51-60].

Adaptive Supply Chain Optimization: Real-time visibility and data-driven decision-making are necessary for efficient logistics in the current evaluation, given the complex supply chains. IoT's role in supply chain optimization includes connected sensors, GPS tracking, and AI-powered analytics to monitor Inventory, track shipments, and predict demand fluctuations. Through an adaptive approach, industries can tune the supply chain operation without causing delays, leading to waste and delays depending on how they tune [61-70].

4. Taxonomy of IoT Challenges and Solutions in Industry 4.0

Below a structured taxonomy is presented to classify the major challenges of IoT adoption in terms of classification of their possibilities of mitigation.

Category 1: Security and Privacy Concerns
Challenge: Cyberattacks originated from IoT networks ([7], [12]).

Solution: The solution to the IoT network vulnerabilities can be the AI powered threat detection and blockchain based security ([13], [29]).

Category 2: Scalability and Infrastructure Constraints

Challenge: Cloud based IoT systems have high computational demands and latency. ([19]).
Solution: Real time data processing using edge can be one of the solutions to this ([24]).

Category 3: Interoperability and Standardization Issues
Challenge: Difficulty in integrating IoT devices based on the lack of standardized IoT communication protocols ([22], [24]).

Solution: This can be resolved through development of universal IoT architecture frameworks ([19]).

Category 4: Predictive Maintenance and Operational Efficiency

Challenge: The maintenance strategies are not efficient and lead to unplanned downtime ([7], [14]).

Solution: AI-integrated predictive maintenance with IoT sensors can be a solution to this ([17]).
Flowchart Representation of the Proposed Framework
An example of the proposed Integrated IoT Security and Efficiency Framework is in the form of a flowchart that is outlined in Figure 1. This offers a holistic approach to solve IoT issues of industry 4.0 in security, scalability and interoperability to achieve better results.

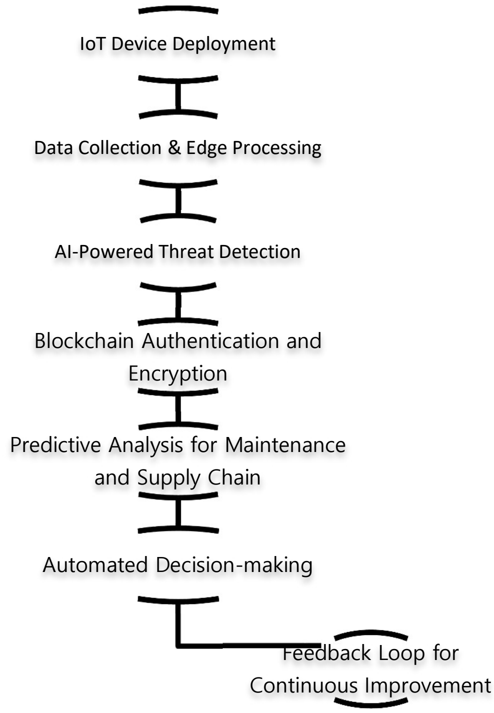

Figure 1: Flowchart to solve IoT issues of industry 4.0

5. Conclusion and recommendations

IoT implementation in Industry 4.0 has revolutionized industrial operations, enabling automation, real-time data exchange, and greater predictability. IoT is a core enabler for improving operational efficiency, minimizing downtime, and increasing resource utilization as industries transform towards ecosystems of interconnected smart manufacturing. To explore the future of industrial automation enabled by IoT, AI, blockchain, and edge computing, the literature review provides insights into decision-making, predictive maintenance, and supply chain resilience. However, several challenges remain, including cybersecurity risks, scalability issues, and interoperability concerns. As industrial environments integrate IoT, there are more avenues for cyber threats, such as data breaches, ransomware attacks, and unauthorized access, which are amplified. According to studies, more than 60% of industrial IoT deployments have known security vulnerabilities stemming from a lack of encryption, access control mechanisms, and network authentication protocols. To address these risks, industries need a robust cybersecurity framework for risk detection, authenticated by blockchain and multi-layered encryption. The other big challenge in the IoT industry is the scalability of connected systems. With the increasing number of IoT devices, the computational demand and latency problem of centralized cloud processing become more severe. It can provide a viable solution by placing data processing closer to the device and enabling real-time decisions at the device level. Edge computing adoption in Industry 4.0 enables decreased reliance on cloud-based infrastructure, faster response times, and increased overall system reliability. Further research will focus on utilizing the most effective edge computing framework for large-scale industrial IoT deployments. The key barrier to an interoperative integration of the IoT remains. There is a lack of standardized communication protocols and interoperability issues when exchanging data across different industrial platforms. By developing universal, open-source IoT frameworks and communication standards, we can solve this challenge so that the industrial ecosystem can be served by IoT devices from different manufacturers with seamless communication. Standardized protocols such as MQTT, OPC UA, and CoAP are required to ensure the reliability of communication between connected workers in Industry 4.0. Cost issues in IoT adoption in Industry 4.0 must also be considered alongside technological challenges. The cost savings from IoT-driven solutions, such as automation and predictive maintenance, tend to accrue over the long term, but there is a significant initial investment in infrastructure, workforce automation, and system upgrades. One important constraint that SMEs have in implementing IoT technologies is a lack of funds. There should be efforts by governments and industry leaders to reduce or address financial barriers and to develop policy frameworks and training programs to encourage IoT adoption across all levels of industry. In this view, a new Integrated IoT Security and Efficiency Framework has been proposed to tackle the major challenges of IoT deployment. The industries can improve the reliability, efficiency, and security of IoT networks using AI-enhanced security measures, edge computing, standardized protocols, blockchain-based security solutions, predictive maintenance, and adaptive supply chain optimization. This framework emphasizes a proactive cybersecurity approach, real-time data processing, and seamless device interoperability, while ensuring the maximum benefits of IoT in the context of Industry 4.0. To provide further insight into the application of this framework, the study illustrates this with a taxonomy of IoT challenges. Based on these, challenges are categorized into four key domains: security and privacy concerns, scalability and infrastructure constraints, interoperability issues, and predictive maintenance optimization. Solutions for each technology category are mapped to corresponding technological solutions, such as AI-based threat detection, blockchain-based authentication, edge computing, AI-based predictive maintenance systems, etc. It offers a structured approach for industries looking to roll out IoT solutions and address ahead-of-the-curve challenges. In addition, the aforementioned flowchart in Figure 1 simulation is also provided in the Integrated IoT Security and Efficiency Framework to designate the critical steps in industrial IoT system deployment, security, and optimization. Firstly, the flow chart outlines the requirements for real-time data collection using AI-based threat detection, blockchain authentication, predictive analytics, automated decision-making, and continuous system optimization. This approach provides detailed information of a particular kind, enabling industries to uniformly adopt IoT technology, mitigate risks, and increase overall efficiency within the organization. Future research would then incorporate the work presented, integrating digital twin technology with IoT systems to produce real-time virtual representations of industrial processes. Finally, in this context, IoT is taking center stage in the Fourth Industrial Revolution in industrial operations, serving to improve them through innovation, efficiency, and intelligence. But implementation is not as straightforward as that and therefore needs addressing cybersecurity threats, scalability issues and interoperability challenges. The taxonomy and flowchart of the proposed framework support a comprehensive strategy to eliminate the mentioned barriers and realize the full potential of IoT for Industry 4.0. By enabling technology providers and policy collaboration, the future of smart manufacturing can come to fruition as the system moves from less connected, more vulnerable, and less sustainable manufacturing to a more connected, resilient, and sustainable manufacturing ecosystem.

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