

IoT-Enabled RFID in Supply Chain Management: A Comprehensive Survey and Future Directions

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Abstract

Radio frequency identification (RFID) has emerged as a pivotal technology in supply chain management (SCM), significantly enhancing its efficiency and effectiveness. When integrated with the internet of things (IoT) to form RFID-IoT, this technology brings transformative advancements to SCM, enabling automated sensing, pervasive computing, and ubiquitous data access across the entire supply chain, from manufacturers and distributors to retailers and consumers. This integration facilitates real-time identification and monitoring of products, enhances various processes, improves logistic tracking, and ensures better product quality management. Despite its promising benefits, the adoption of RFID-IoT in SCM faces several challenges, including technical complexities, data security concerns, and high implementation costs. However, the future potential of RFID-IoT technology remains substantial. It is anticipated that further integration with other emerging technologies, such as block chain and artificial intelligence, will lead to more comprehensive and robust SCM solutions, offering unprecedented levels of transparency, efficiency, and automation in supply chain operations.

Keywords

Radio Frequency Identification, Supply Chain Management, Internet of Things, Logistic Tracking, Data security, Wireless Sensor Networks, Block Chain, Artificial Intelligence, RFID-IoT Integration, Real-Time Supply Chain Monitoring, Inventory Management Automation, Logistics Optimization

1. Introduction

Health care, security, agriculture, environmental monitoring, and supply chain management are just a few of the many industries that have benefited from radio frequency identification (RFID) solutions during the past half century. By utilizing radio frequencies, RFID technology is able to recognize distinct identifiers from great distances. In the past, radio frequency identification (RFID) worked in a manner similar to other types of sensors; it would generate and receive electromagnetic fields between an RFID reader and a tag, allowing for remote monitoring, multi-sensing, and localization. Detection and identification are RFID's primary functions [1], which highlighted that RFID's capacity to connect physical things with their digital data is a major benefit. This is because RFID can bridge the gap between the physical and information realms. Several sectors can benefit from RFID's improved traceability since it allows automatic sensing and recognition across longer distances than barcodes, which need line-of-sight alignment.

The widespread computing capacity of Wireless Sensor Networks (WSN) and the superior identifying capabilities of Radio frequency identifying (RFID) have accelerated the growth of the internet of things (IoT). The primary objective of the internet of things (IoT) is to facilitate the worldwide exchange of data by means of a huge network that integrates numerous sensor devices, such as radio frequency identification (RFID) readers, global positioning systems (GPS), and communication networks. Wireless sensor networks (WSNs) and radio frequency identification (RFID) are crucial to the internet of things (IoT) because WSNs provide dispersed, ubiquitous wireless systems and RFIDs turn physical items and environments into digital data. Internet of things (IoT) promotes a worldwide interconnected network where any item can be identified and used as a resource by combining RFID's superior sensing capabilities with WSN's extensive ubiquity. The combination of radio frequency identification technology with the internet of things has changed several industries, most notably supply chain management (SCM), by making devices much more compatible with one another and with other applications [2].

Managing raw materials, suppliers, organizations, and consumers are all essential components of supply chain management (SCM). Supply chain management systems are created to bolster company strategies that aim to maximize shareholder profits [3]-[8]. When it comes to supply chain management, RFID-IoT is vital since it improves data collecting, identification, process improvement, and optimization, even in the most unpredictable of settings. Also, RFID-IoT makes it easier for devices to interact with each other and for people and their surroundings to be interdependent. All SCM procedures run well because of these interconnections. Furthermore, RFID-IoT solutions address critical challenges in supply chain operations, such as achieving precise real-time tracking [9]-[16], enhancing process automation [17], and improving demand forecasting accuracy [18]. By enabling comprehensive asset management, loss reduction, and heightened transparency, RFID-IoT reinforces the reliability and efficiency

of SCM systems, underscoring the significance of this research topic [12]-[16] [19]-[23].

Many academic articles have been published on the subject of RFID-IoT, indicating a major increase in research interest in this area. From 2010 to 2019, the number of articles on RFID-IoT was shown in **Figure 1**, which is based on Google Scholar searches. There has been a noticeable uptick since 2015, when the annual output of articles typically surpassed 1000. The majority of these research centre on important domains including retail, inventory management, shipping & distribution, and manufacturing. The increasing amount of papers in the field of RFID-IoT research in supply chain management demonstrates the expanding importance and promise of this field.

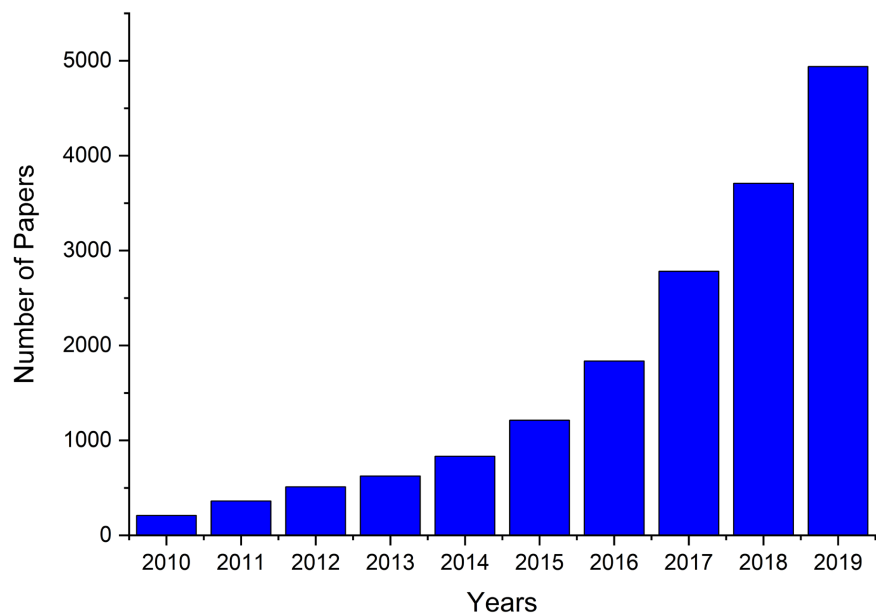


Figure 1. Yearly total of RFID-IoT items [24].

This paper delves into the literature on RFID-IoT in supply chain operations, offering an overview of the technology's background and valuable insights into the anatomy of previously proposed methods. It highlights current limitations and explores future potential. Given that these solutions have been around for over a decade, a review of past proposals is essential to provide researchers and practitioners with a comprehensive understanding of the technology [21] [25]-[27]. The objectives of this paper are: to assess the advancements of RFID-IoT technology in supply chain management (SCM) in terms of effectiveness, interoperability, scalability, and compatibility; to identify the challenges faced by current approaches in SCM; and to discuss anticipated future developments in RFID-IoT technology. Specific results and practical application. This paper also aims to provide a structured evaluation of RFID-IoT systems, clarifying the criteria used to measure their effectiveness, interoperability, scalability, and compatibility in SCM settings. Through these objectives, the study intends to guide readers in

understanding the relevance and applicability of RFID-IoT advancements in addressing real-world SCM challenges [25] [28].

There are a number of important parts to the paper. The second section gives a brief summary of RFID-IoT. After this, Section III explores the supply chain management RFID-IoT techniques. Section IV delves into the present constraints of RFID-IoT systems and investigates their prospective and future trajectory within SCM. The last section of this review article provides a brief summary of its main arguments and conclusions.

2. An Overview of RFID-IoT for Supply Chain Management

A non-contact and automatic identifying system, radio frequency identification (RFID) employs electromagnetic radiation to recognize, track, and uniquely identify a wide variety of items, including vehicles, components, commodities, and personnel. The three main parts of a radio frequency identification (RFID) system are the tag itself, the reader, and the database that keeps track of the UI for all the items that have been tagged. Passive and active RFID tags are the two main types. Passive tags derive their energy from the RFID reader's electromagnetic field, rather than from an internal power source. Active tags, on the other hand, can transmit signals over longer distances since they have their own power source, such as a battery. Because they are always transmitting signals to the reader, active tags are perfect for tracking locations in real time. Passive tags, on the other hand, are utilized when cheap deployment necessitates tagging several things. They are more affordable and possess data density capabilities comparable to active tags.

Low rate, high frequency, ultra-high frequency, and microwave signals are the four main types of operating frequencies that determine an RFID reader's read range. RFID and barcodes are comparable in that they both record distinct serial numbers for the purpose of product tracking. But radio frequency identification (RFID) offers a greater data store capacity and can identify specific objects with unique serial codes utilizing radio waves, unlike barcodes. Wireless sensor networks are necessary for RFID deployment to go off without a hitch. When compared to wired networks, RFID becomes more scalable, portable, and cost-effective with the addition of WSNs. The internet of things (IoT) links real-world and digital things via data gathering, ingestion, and communication technologies; two key enabling technologies of this network are radio frequency identification (RFID) and wide-area network (WSN). The internet of things (IoT) is a three-layer system that is changing the way gadgets work in different surroundings by making them remotely available to people through their networks and applications [29]-[31].

The significance of RFID-IoT technology in supply chain management (SCM) is crucial because it allows for the automatic identification of trustworthy data and the facilitation of communication through the internet in order to monitor the status of goods, inventories, equipment, machinery, and personnel. With RFID-

IoT, users can keep tabs on every step of the production process and get timely, relevant feedback no matter what's happening [32] [33]. As a result, the supply chain becomes much more efficient, cutting down on wasteful spending and losses. For example, it lessens the possibility of resources like raw materials, logistics vehicles, and laborers being scarce [8] [30] [34]. The difficulty in accurately estimating time and money spent due to the lack of integration and combination of processes finished at each level is a big problem in supply chain management [35]-[44]. This problem is solved by RFID-IoT, which provides automatic intra- and interconnection of machines, processes, stages, and the environment. This technology allows for the smooth transfer of data over the internet, which improves transparency all the way through the supply chain and leads to a more efficient workflow. Production, transportation, inventory management, and retail tracking are the four main phases of RFID-IoT deployment. Recent publications on RFID-IoT applications in these four critical domains will be examined in this study.

3. Management of the Supply Chain with an RFID-IoT System

Low-power and cost-efficient, radio-frequency identification (RFID) is a non-contact automatic identifying technique. Because of its many useful features, it is finding more and more uses in supply chain management (SCM) around the world. Internet of things (IoT) integration improves this by making data collecting and sharing possible over the Internet, leading to an RFID-IoT system that is secure, interoperable, and runs smoothly. This integration creates many new possibilities in the supply chain. There are four main sectors in which RFID-IoT enhanced supply chain systems can be classified, as shown in **Figure 2**: production, shipping and distribution, inventory, and retail. Analyzing scientific articles to study the methodology and applications within these four categories, we aim to provide readers with a full grasp of the impact of RFID-IoT on supply chain management.

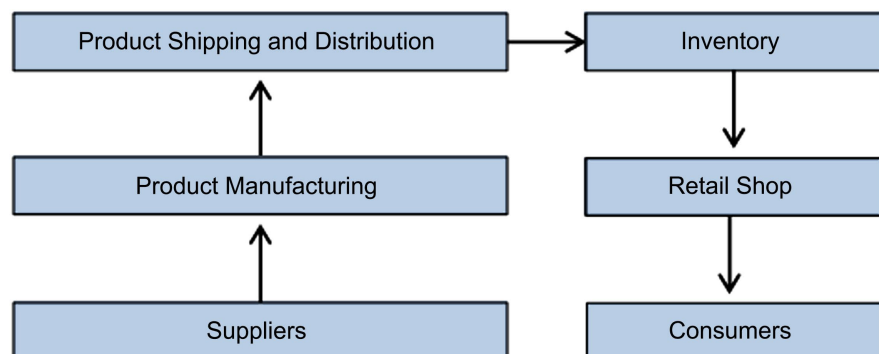


Figure 2. A supply chain system that uses RFID and the Internet of Things.

Table 1 shows how RFID technology is classified according to its operating frequency and the kinds of applications it can manage.

Table 1. RFID features, frequency ranges, and SCM implementations [9].

RFID frequency range of functionality	RFID properties	RFID frequencies	Read range	Transmission rate	Applications
Low frequency (LF) 30 - 300 kHz	Passive	125 - 134 kHz	Short	Slow	Retail counting and manual warehouse
High frequency (HF) 3 - 30 MHz	Passive	13.56 MHz	Medium	Medium	Computerized object tracking
Ultra-high frequency (UHF) 300 MHz - 3 GHz	Passive	433 MHz and 865 - 956 MHz and 2.45 GHz	Long	Fast	Monitoring and updating logistics changes for several sites
Microwave 2 - 30 GHz	Active	2.45 - 5.8 GHz	Very long	Very fast	Observation in real time of workers, assets, and works in progress (WIP)

3.1. Manufacturing Tracking

There have been a lot of studies looking at how manufacturing supply chains might benefit from RFID-IoT technology to improve efficiency by using data insights from sensor networks. An intelligent trolley and process utilising real-time navigation were introduced by [45] as part of an active material handling approach. We aim to reduce task deviations and errors as much as possible. To enhance machine-to-machine (M2M) communication, the approach makes use of RFID's active detection capacity, interactive procedure flow, and connection with the internet of things (IoT). Reduced mistakes in handling through automated real-time routing is one way the optimized approach improves the effectiveness of bulk tracing and tracking. In addition to satisfying the needs of mass production, this results in reduced transportation costs.

Also, reducing downtime expenses, handling processing faults, and handling product recalls all depend on automated part identification and tracking in the automotive industry. In 2016, [46] created a system for tracking crankshafts with the use of a novel RFID-encased bolt. The system's inexpensive UHF RFID active tag and optimized reader antenna architecture are ideal for metal applications, and it's built to endure tough conditions. Similar engine components can also reuse the RFID bolt. By utilizing IoT technology, local servers are equipped to store real-time data pertaining to production, assembly, environment, and service. When compared to systems that rely on cameras, the study found that the RFID-IoT system for crankshaft assembly was more cost-effective.

The materials used in production must be of high quality and safe for human consumption. Acquiring information on the composition of materials and any incompatible constituents prior to distribution is crucial in order to fulfill the requirement for improved quality and safety. In order to keep tabs on everything from seeds to food additives, [47] used internet of things (IoT) sensors, such as radio frequency identification (RFID) as well as near field communication (NFC). Automated, efficient, and real-time data collecting is made possible by an internet

of things application, which streamlines the process of tracking raw materials. Product safety and efficacy are both improved by using this data to confirm the attributes of ingredients, such as their chemical makeup.

Using radio frequency identification (RFID) and quick response (QR) codes, Li, *et al.* [48] created a practical and cost-effective method for monitoring pre-packaged food in real-time. For mass production, this combination was shown to be the most cost-effective. In addition to counting things, the system can identify harmful components, excessive additives, and expiration dates. It has validation and alert systems to find problems and let people react quickly, especially when it comes to food safety and quality.

3.2. Shipping and Distribution Tracking

Product shipment and distribution tracking has been the subject of a great deal of writing in the field of supply chain management. Vehicle leadership, asset and resource management, and the estimation of dispatch and arrival timings based on current data streaming are the primary foci of these research, which span the full product lifecycle, from suppliers to end users.

As an example, Qiu, *et al.* [49] emphasized how real-time data can improve logistical transparency and visibility. They zeroed in on logistical management at supply hubs that house and transit warehousing for numerous firms, and they spoke about vehicle management for order dispatch and pick up inside industrial parks. They built an end-to-end system architecture using RFID and the internet of things to track and share data about company services and physical assets. Efficient deployment, user-friendly processes, flexible access, and straightforward data formats such as Extensible Markup Language (XML) are the goals of this infrastructure.

The Inland Shipping Management Information System (ISMIS) was also suggested by Wu *et al.* (2011) with the aim of bettering such management. ISMIS utilizes key technologies including RFID, the internet of things (IoT), and cloud computing in conjunction with Wireless Sensor Networks (WSN) to deliver up-to-the-minute data on inland waterway traffic, conditions in the environment, bridge information, and vessel states. Through the elimination of informational roadblocks and delays and the enhancement of data transparency, this design has enhanced managerial efficiency.

Meanwhile, Ding, *et al.* [50] laid up a thorough plan for web-based production to retail transportation outsourcing. In order to provide improved decision-support instruments for item scheduling, dispatch and delivery time, order management, and RFID-enabled social manufacturing system (RFID-SMS) integration of real-time transportation and production data was introduced. They also suggested TLBO, or Improved Teaching-Learning Based Optimization, a meta-heuristic approach to transportation and production cost minimization.

3.3. Inventory Tracking

A wide variety of functions, such as identifying goods, equipment maintenance,

environmental monitoring, and labor tracking, are covered in articles on RFID-IoT utilization for inventory tracking. The goal of Tejesh and Neeraja [51] real-time interior warehouse inventory system was to achieve very efficient inventory management by identifying and monitoring products. Due to its adaptability and durability, RFID technology was chosen over barcodes. Because of the reduced interference and maintenance costs, passive tags were chosen. A Raspberry Pi 3, an open-source internet of things (IoT) platform called NodeMcu, and a Wi-Fi module called ESP8266-01 make up the system. Their prototype easily resolves inventory inaccuracies by displaying product characteristics in a prepared table, including tag number, storeroom setting, time, and description.

By classifying products according to their chemical qualities, Trab, *et al.* [52] developed a new storage utilization method for safer product management. The products were categorized as combustible, explosive, oxidizing, health hazardous, toxic, damaging, or corrosive. To provide safe storage, these groups adhere to compatibility standards; for example, combustible and toxic substances can be kept together. In order to illustrate product categories and compatibility, the authors provided a mathematical model; they stressed the significance of properly storing dangerous substances. In addition, they created a communication model that makes use of RFID and the internet of things to facilitate interactions in the inventory area between things, people, and the environment. This method improves security and makes storage more efficient by decreasing the amount of time products need to be stored.

By adding mobile, tractable shelves, Zhou, *et al.* [53] suggested a novel method for retail tracking. They achieved this state of perfection in inventory management by integrating RFID for shelf location tracking and IoT for real-time data streaming to a server. Lowering inventory inaccuracies, trip expenses, and wait times for single-trip demands, this system enables effective item dropping off and pickup according to demand within the coverage area. Simplifying the management of complicated operating inventories and warehouses is the primary goal of their approach.

3.4. Retail Tracking

Not only is operational efficiency and technical innovation demanded in the retail sector, but the competition is fierce. As RFID-IoT technology has developed and matured, it has becoming widely used in a variety of consumer applications inside retail. This involves preventing the sale of fake goods and improving the shopping experience for customers by providing them with up-to-the-minute product information and allowing them to pay more quickly.

The development of an affordable ultra-high-frequency RFID reader utilizing printed circuits was the focus of Xiao, *et al.* [54]. Using screen printing with highly conductive ink, they created an excellent RFID antenna that outperformed traditional chemical etching techniques, particularly on metal shelves and other difficult surfaces. The deployment expenses of RFID in large stores can be reduced

with this innovation.

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When it comes to RFID-IoT security measures, Tewari and Gupta [55] suggested a reciprocal authentication protocol for internet of things (IoT) devices, particularly RFID readers and tags. Their protocol has benefits in terms of cheap computing, storage, and communication costs; it is based on bitwise operations. It successfully automates operations with limited resources by ensuring safe and efficient authentication for passive tags.

Recent research on RFID-IoT smart retailing by Tan [24] presented a system to address practical issues encountered by shoppers. Personalized radio frequency identification (RFID) sensors, gateways, cloud computing, and mobile device technology are all part of their solution. By delivering up-to-the-minute product details, specials, and navigational aid, an intuitive Android app improves the shopping experience. In addition to automating and integrating all aspects of retail operations, this system also boosts store efficiency economically. These developments highlight how RFID-IoT technologies have the ability to revolutionize the retail industry by improving productivity and customer delight.

4. Specific Results and Practical Application Effects of RFID-IoT Technology

The integration of RFID-IoT technology has had a significant impact on supply chain efficiency, logistics tracking, and product quality management, resulting in measurable improvements and practical benefits in a variety of applications. RFID-IoT technology improves inventory accuracy and streamlines warehouse management by automating data collection, and lowering manual labor and operational costs [56]. Real-time tracking enables businesses to continuously monitor product movement, allowing for quick response to potential delays, theft, or misplacement [57]. This visibility in logistics improves route optimization, reduces fuel consumption, and shortens delivery times, all while enabling better demand planning and accurate forecasting via data-driven insights [58]. Furthermore, RFID-IoT helps with product quality management by ensuring strict environmental monitoring for temperature-sensitive goods like food and pharmaceuticals, which reduces spoilage and ensures compliance with safety standards.

Furthermore, RFID-IoT's unique identifiers provide a strong solution to counterfeiting, reinforcing brand integrity in industries such as luxury goods and pharmaceuticals. Overall, RFID-IoT technology's practical effects reflect its role in creating a more responsive, transparent, and resilient supply chain, resulting in increased operational efficiency, customer satisfaction, and cost-effectiveness [59].

5. Economic and Social Impact of RFID-IoT Technology in Modern Supply Chains

The incorporation of RFID-IoT technology into supply chain management provides significant economic and social benefits, aided by supportive policy frameworks and rising market demand. Economically, RFID-IoT increases efficiency by automating tracking, inventory management, and quality control, resulting in lower labor costs, fewer errors, and fewer losses due to theft or misplacement [17]. This efficiency extends to logistics, where real-time monitoring optimizes routes, reduces fuel costs, and improves demand forecasting, ultimately supporting profitability and allowing businesses to offer competitive pricing. Socially, RFID-IoT promotes transparency and safety by providing accurate product tracking, which is critical for sensitive goods such as food and pharmaceuticals, thereby protecting consumers and building trust [60]. Furthermore, the technology promotes environmental goals by reducing waste and facilitating sustainable practices throughout the supply chain. RFID-IoT adoption is driven by policy initiatives focusing on digital transformation, data transparency, and sustainability, particularly in industries regulated for safety and anti-counterfeiting, such as healthcare and food. The growing consumer demand for safe, ethical, and sustainable products drives market growth, as businesses recognize the technology's role in meeting modern transparency and efficiency standards. In essence, RFID-IoT technology is expected to play an important role in developing resilient, sustainable, and consumer-responsive supply chains.

6. Present Difficulty and Prospects for RFID-IoT in the Future

From straightforward tracking and tracing systems to intricate value networks that incorporate environmental, M2M, and machine-to-human interactions, modern supply chains have experienced a dramatic evolution. All parties involved in the supply chain, from manufacturers to distributors to retailers, can now draw significant competitive benefit from this innovation. But it has also made it very difficult to build supply chain management (SCM) solutions that are both practical and flexible.

Radio frequency identification (RFID) and the internet of things (IoT) are key to this change because they allow sensors, inexpensive processors, and omnipresent computing to connect all parts of the supply chain seamlessly. The goal of integrating these technologies is to make the supply chain more transparent, make better use of limited space for inventory management, and provide better experiences for customers in retail settings.

Concerning RFID-IoT hardware is one of the main issues brought up in the present literature. Improving RFID tag and scanner designs with a focus on sensitivity, adaptability, practicality, and reliability is an urgent matter. To fix the current problems with product tracking and traceability, new developments will likely concentrate on making things smaller, using less energy, having capabilities built in, and being easy to integrate with other technology.

Problems with compatibility and interoperability between old and new systems are also major obstacles. Though they perform admirably on a grand scale, many of the suggested solutions falter when it comes to reworking and sustaining intricate data pipelines and network topologies. These obstacles highlight the need for effective data management strategies and simplified integration frameworks in terms of time, money, and resources.

The difficulty of handling enormous data quantities within unified networks is being worsened by the expansion of IoT devices. System delays, communication mistakes, and user conflicts are some of the complications brought about by connected devices' ability to gather data in real-time. Tackling these difficulties necessitates a strong foundation that can manage massive amounts of data being transmitted and processed, backed by knowledgeable staff and powerful computer technology such as CPUs and GPUs.

Furthermore, network standards, identification methods, data formats, security procedures, and communication protocols must all be standardized in order for RFID-IoT systems to be developed. Guidelines like ISO 11784/11785 for animal monitoring and ISO 14443 for electronic payments are issued by international agencies like the International Organization for Standardization (ISO). However, global standardization efforts are impeded by disparities in legislative frameworks among countries. In order to guarantee compatibility and security across various supply chain settings, it is crucial to harmonize these standards.

There are significant privacy and security risks in the RFID-IoT ecosystem. Possible security risks include eavesdropping, tampering, and unauthorized synchronization when readers with RFID and tags are connected wirelessly. Reliable authorization modules designed specifically for RFID-IoT systems are an essential component of strong security measures to counter these threats. In order to protect supply chain operations from cyber threats and unauthorized access, it is crucial to ensure the confidentiality and integrity of data flows.

The majority of the research is devoted to discussing how to put IoT techniques into practice with systems that have sensing capabilities for data transfer. But existing systems use a mix of technologies, which drives up the price of developing infrastructure. There are compatibility issues with current infrastructures and inflated adoption costs due to operational expenditures and the difficulty of integrating new systems. Efficient project processes require careful coordination to manage supply chain costs and optimize resource allocation.

An important step forward, RFID-IoT holds the promise of adapting supply chains to the ever-changing demands of customers and their orders. Company size, profitability of products, and middleware and hardware expenses are some of the variables that affect the potential benefits of RFID-IoT adoption. In order to weigh the benefits of adoption against their costs, it is essential to do a comprehensive Return on Investment (ROI) study that measures these important elements. This will help with making informed decisions.

Analyzing all of the data is crucial for making better use of resources and saving

money. Hu, *et al.* [61] and Wang, *et al.* [62] are two examples of studies that suggest RFID-IoT solutions for supply chain data processing and exchange. However, these studies frequently fail to account for computing costs and effectiveness of storage. The advent of cloud computing, however, offers a practical alternative. Microservices for on-demand computing are available on cloud platforms, which is great for cost-effective data sharing and system integration. Cloud computing allows developers to avoid the high costs of developing infrastructure in-house, which include software, hardware, and human resources. Quick Proof of Concept development across different apps with low monetary outlay and resource commitment is made possible with cloud services like Google Cloud Platform's flexible "pay-as-you-go" models, which do not need upfront or termination fees.

A paradigm shift is underway in the optimization of supply chain efficiencies, with a focus on scalability, cost-effectiveness, and adaptability in an ever-changing corporate landscape, as cloud-based solutions continue to evolve.

7. Conclusion

The integration of radio frequency identification (RFID) with internet of things (IoT) technology has automated various applications, enhancing them with advanced sensing, identification, processing, communication, and network capabilities. This paper conducts a comprehensive review of recent research on the application of RFID-IoT in supply chain management (SCM). It begins with an overview of RFID, wireless sensor networks (WSN), and IoT technologies, emphasizing their foundational roles and significant contributions to SCM over the past decade. Following this, the paper delves into a detailed discussion on the utilization of RFID and IoT technologies in SCM, illustrating their impact on improving efficiency, transparency, and traceability within supply chains. The review identifies and elaborates on the current challenges faced by RFID-IoT implementation in SCM, such as issues related to data security, integration complexity, and scalability. Additionally, it explores potential future research directions and advancements that could address these challenges. The paper concludes by highlighting the transformative potential of combining RFID-IoT with other emerging technologies, suggesting that such integration could lead to substantial improvements and innovations in SCM practices, ultimately driving greater efficiency and effectiveness in the industry.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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