Review

An investigation on real-time insights: enhancing process control with IoT-enabled sensor networks

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Abstract

The Internet of Things (IoT) and sensor networks have significantly advanced process monitoring and control in multiple sectors, including manufacturing, agriculture, healthcare, and smart cities. Given the substantial volume of IoT-generated data, design-oriented solutions are necessary to accelerate data processing and improve scalability and flexibility. This article provides a comprehensive examination of the principal applications, technology, challenges, and future trajectories of IoT and sensor networks in process control as the control and monitoring of processes across industries are being transformed by the accelerated development of the IoT and sensor networks. Nevertheless, its pervasive adoption is impeded by obstacles such as data overload, scalability, and energy efficiency. This study is an investigation that presents a comprehensive framework for the integration of IoT-enabled sensor networks into real-time process control systems, thereby addressing these issues. We illustrate methods to enhance the collection, processing, and decision-making processes by studying advanced communication protocols such as MQTT and CoAP and key enabling technology of sensor networks. By conducting case studies of smart cities, agriculture, healthcare, and production, this investigation has extensive implications, enabling various industries to achieve enhanced operational efficiencies, robust scalability, and improved safety. Despite significant breakthroughs, challenges such as security, energy efficiency, and scalability remain to be addressed. Finally, we have presented advanced technologies capable of addressing these challenges and shaping the trajectory of IoT-based process management systems, including block chain, 5G, and AI integration and discussed future implication of study.

Highlights

- Discusses use of sensor networks and IoT in development of smart manufacturing, agriculture, cities, buildings, logistics frameworks etc.
- Contributes to sensor network literature in areas of real-time customer behavior monitoring and real world applications.
- Emphasizes on sustainability with focus on IoT solutions that bolsters energy conservation and ecological initiatives.

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1 Introduction

Across all industries, process management and monitoring are critical for maximizing productivity and guaranteeing efficiency and safety. Historically, manual interventions and wired control systems have been used to accomplish this. Nevertheless, new avenues for improving and automating process monitoring have become available due to the quick development of sensor networks and the Internet of Things. The Internet of Things, or IoT, is a network of physically connected objects that can speak with one another via the internet. Actuators, sensors, microcontrollers, and microprocessors are physical devices that connect to the Internet through an IoT gateway rather than directly [1].

IoT infrastructure refers to the comprehensive system of infrastructure. Consider a home lighting system, for instance, in which every switch is linked to the main controller via an internet connection. With its incorporated Internet of Things technology, the smart switch board can also be referred to as a linked board, supporting a variety of products and their working. Also, by pooling their collective expert knowledge, they may be able to offer more sophisticated services [2]. Researchers focus on foundational elements for managing large data in various big data system research projects, including specific applications, technology, procedures, and standards (finance, social web, etc.). Nonetheless, a wide range of infrastructure and technologies are used to carry out the aforementioned real-world functions. As a result, certain benefits are increasingly modelled into data-intensive systems. Numerous studies have shown that current methods for handling big data system issues must address infrastructure-based computation for data overflow, which includes cloud computing, granular computing, and bio-inspired computing.

Gathering data is the first stage in building a big data system. Wireless Sensor Networks (WSNs) can obtain important data elements from a variety of data-producing sources. Massive amounts of Sensor Network (SN) records and physical network factor monitoring are part of WSN and this data is gathered at the sink node [3]. Furthermore, wireless networks and their limited capacity causes crisis that sends data to the sink node. However, big data benefits from efficient network processing and data aggregation. Examining research that bridges massive data sets and wireless sensor network systems while addressing WSN technology shortcomings and improving performance is necessary. From the standpoint of data utilization, IoT data provides context-aware computing, similar to pervasive and ubiquitous computing. Therefore, WSNs need to be effectively studied in light of the big data dilemma [4].
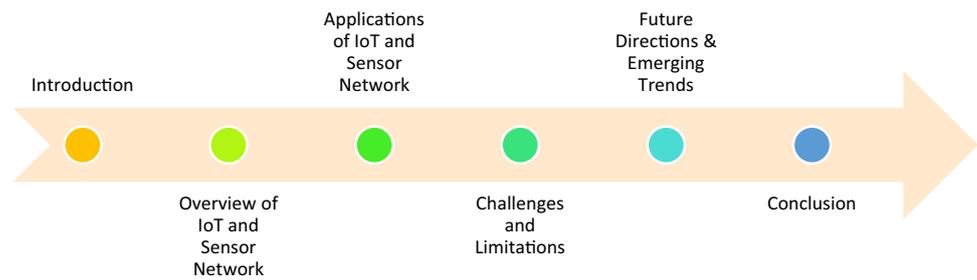
Furthermore, massive amounts of data on wireless networks can be handled via wireless big data systems. Researchers focused on wireless infrastructure such as data-driven network optimization, data-aided transmission, and applications over layered architecture (as seen in data layers, transmission, network, and applications) to demonstrate entire systems. They have also highlighted three possible application domains: drones/UAVs, smart grids, and the Internet of Things [5].

In today's digital age, IoT and sensor networks play a key role in modern process control systems. They allow for more automation, boost productivity, and help make choices based on data. While we've seen big steps forward, many industries still struggle to use IoT-enabled sensor networks. They face hurdles like handling huge amounts of data, growing their systems, dealing with power limits, and staying safe from cyber threats. To change industries with IoT, we need to tackle these problems head-on. The push for this study comes from the increasing demand for instant insights across industries like manufacturing, healthcare, farming, and urban development. Traditional control systems often fall short in managing the ever-changing complexities of today's operations. Past reviews have looked at different parts of IoT and sensor networks, but they don't give a full picture of how to blend real-time data analysis, communication methods, and edge computing answers to tackle the main hurdles in setting up IoT [6]. Novelty of this work is how it takes a big-picture look at IoT-powered sensor networks for process control. Unlike earlier studies, this review digs deep into cutting-edge communication protocols such as MQTT and CoAP top-notch IoT platforms and edge computing tech. Furthermore, the study highlights how IoT combines with cutting-edge tech like Artificial Intelligence (AI), Machine Learning (ML), and blockchain to boost security, scalability, and productivity [7, 8]. This research gives In-depth analysis, targeted solutions, real-world relevance, and future outlook. The review intends to examine the state of sensor networks and IoT in process control and monitoring today. We go into the fundamental design, many industry applications, major difficulties, and upcoming developments to provide readers with a comprehensive understanding of how these advancements are changing business. Table 1. Illustrates the comparison of present work with earlier literature. Figure 1 shows schematic design of the manuscript.

Table 1 Comparison with state-of-the-art surveys

Study	Focus area	Key contributions	Limitations	Difference from this study
Sheng et al. (2020)	Industrial IoT	Multi-layer architecture for data management	Lacks focus on energy efficiency	Our study includes energy optimization and AI integration
Jaladi et al. (2021)	Environmental monitoring	LoRaWAN-based low-power sensor nodes	Limited scalability for large deployments	Our study addresses scalability with advanced platforms
Devan et al. (2022)	Healthcare IoT	CoAP-based patient monitoring systems	Privacy concerns and cloud dependency	Our study incorporates blockchain for security
Rajput and Kumaravelu (2023)	Precision agriculture	Sustainability through fuzzy decision-making	High initial setup cost	Our study provides cost-effective solutions with edge computing

Fig. 1 Schematic design of the manuscript

2 Overview of IoT and sensor networks

2.1 IoT architecture

IoT systems are made up of several layers that cooperate to allow data to flow from sensors to applications seamlessly. Four levels comprise the fundamental architecture of the Internet of Things:

- **Sensing layer** Actuators and sensors in this layer gather information from the surroundings. Sensors measure physical characteristics like temperature, humidity, pressure, and motion. Actuator on the other hand, respond to control signals to change settings or turn on/off equipment [9].
- **Network layer** This layer handles data transfer between the data processing units and the sensing layer. It includes network infrastructure and communication protocols that allow devices to be connected [10]. Communication technologies include cellular networks (e.g., NB-IoT), Bluetooth, Zigbee, LoRa, and Wi-Fi.
- **Data processing layer** Once data is collected, it is processed at this layer, either in the cloud or at the edge. Cloud computing provides centralized data processing, storage, and analytics, while edge computing enables real-time processing closer to the data source, reducing latency[11].
- **Application layer** User-facing apps that employ processed data to provide actionable insights, manage operations, or send out alerts make up the last tier. Applications include everything from urban management platforms to industrial automation solutions [12].

2.2 Sensor networks

To deploy WSN for industrial applications, several hard requirements must be met. For example, developing appropriate network topologies, methods, and algorithms to ensure good communication quality and system stability is necessary for monitoring and controlling a given process. Furthermore, industry implementations must guarantee data dependability at all times due to potentially challenging environmental circumstances. Choosing the effective solutions that application-specific WSN architectures should take into account is a difficult task for the WSN designer [13]. While it is challenging to suggest a comprehensive methodology for creating WSNs for industrial use, this study takes into account some of the more prevalent resource limitations of a WSN in this domain, including limited power consumption, resilience, processing capability, and storage [14].

3 The key features of the sensor network

- **Scalability** is used to describe a sensor network's capacity to grow by adding additional nodes that collect information without materially affecting the network's general efficiency. The network should continue to operate efficiently when more sensors are added, preserving processing power and data transfer speeds [15]. This feature is crucial for applications that need wide coverage, such as infrastructure for smart cities or environmental monitoring across big geographic areas.
- **Energy efficiency** is another essential feature of sensor networks. Many sensor nodes are placed in difficult-to-reach or isolated locations where it is difficult to change batteries or maintain a steady power source. Sensor nodes are made

to use as little power as possible to increase the operational lifetime of these networks. Low-power communication protocols are frequently used, and data transmission is optimized to use less energy [16]. Energy-saving strategies like duty cycling in which sensors alternate between active and sleep states, are frequently employed.

- **Reliability** assures accurate and consistent data collection and transmission, even in difficult circumstances. Applications where data integrity is critical, such as industrial process control or healthcare monitoring, require reliability. Sensor networks need to be robust against interference, node failures, and external conditions that could taint the quality of the data. Reliability is frequently improved by implementing error-checking techniques and redundant data transmission pathways [17]**.** Symmetric diagram of sensor networks can also be seen in Fig. 2.

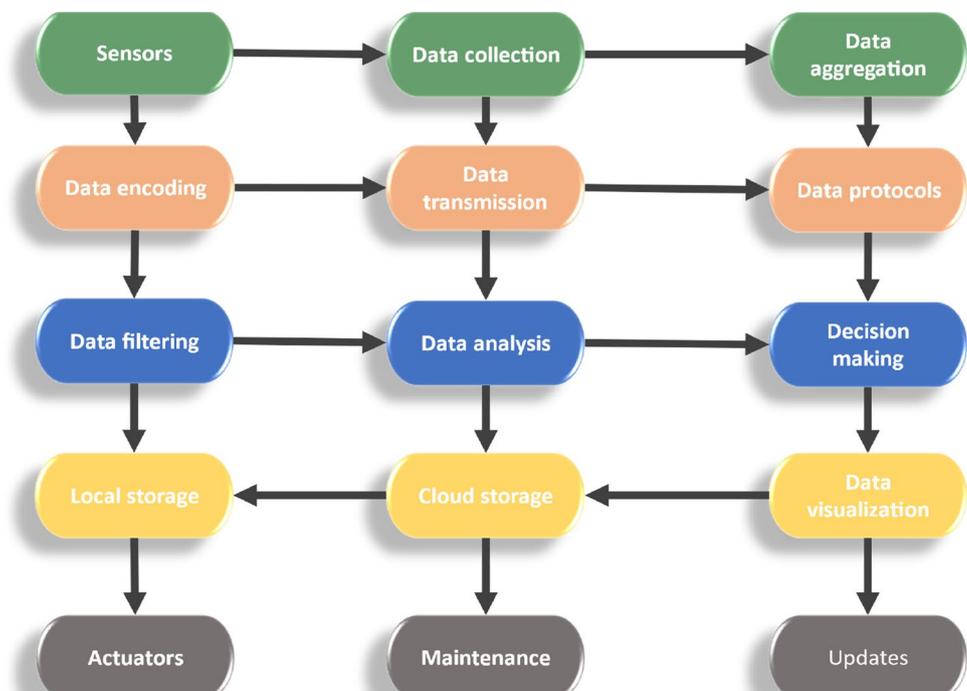## 3.1 Key enabling technologies in sensor networks

Key enabling technologies depend on the situation and domain, and application of different IoT enabling technologies. For instance, adaptable solutions that guarantee the connectivity of a large number of mobile nodes are necessary for smart transportation, on the other hand, honesty and dependability are the main concerns in healthcare [18]. Certain generic technologies are described here in brief according to how they work inside the IoT's layer paradigm.

Perception layer technologies: In the IoT paradigm, the perception layer also referred to as the objects layer is the lowest layer. It comprises a variety of physical devices, such as item identifiers, temperature sensors, position sensors, and humidity monitors, that are in charge of gathering data and taking appropriate action [19]. Important features of this layer is its power consumption and communication capability (i.e., unidirectional or bidirectional). The perception layer technologies are categorized as seen in Fig. 3.
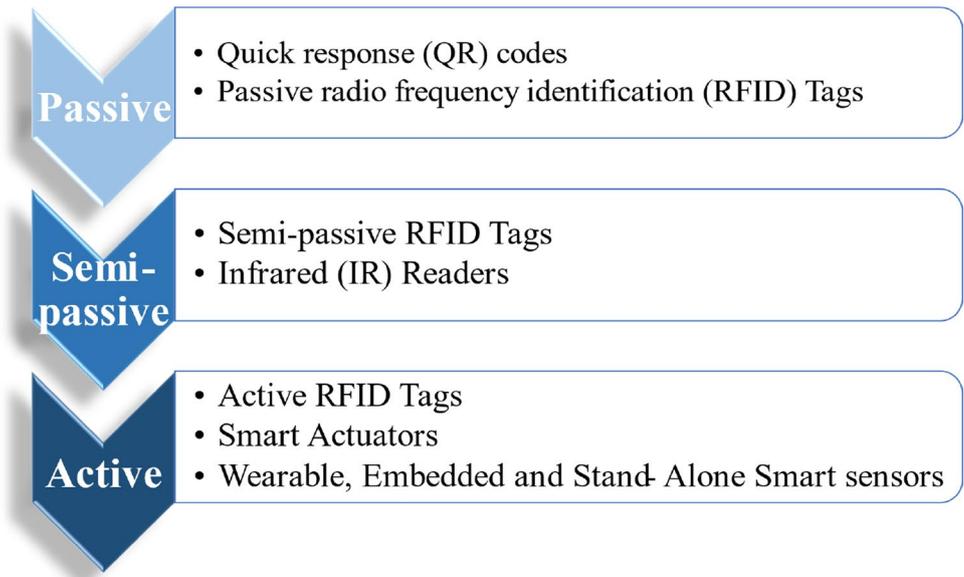
Network layer technologies: The second layer is called the network or object abstraction layer. Because of the technologies it uses to turn the traditional sensors mentioned in the perception layer into intelligent networked nodes, it is referred to as the infrastructure layer. Network layer technologies facilitate safe communication between nodes by making them identifiable across the internet or any local area network [20]. Many of the technologies contained in this layer are also present in the Link, Internet, and Transport layers, the first three layers of the TCP/IP protocol suite. Figure 4 illustrates network layer technology.

Middleware technologies: The core component of the Internet of Things is the middleware layer, sometimes referred to as the service administration layer. It might be associated with the TCP/IP application layer within the IP suite. Internet of Things platforms frequently support the technologies in this tier. This layer lets programmers communicate with heterogeneous objects regardless of the hardware configuration by allowing services to be recognized
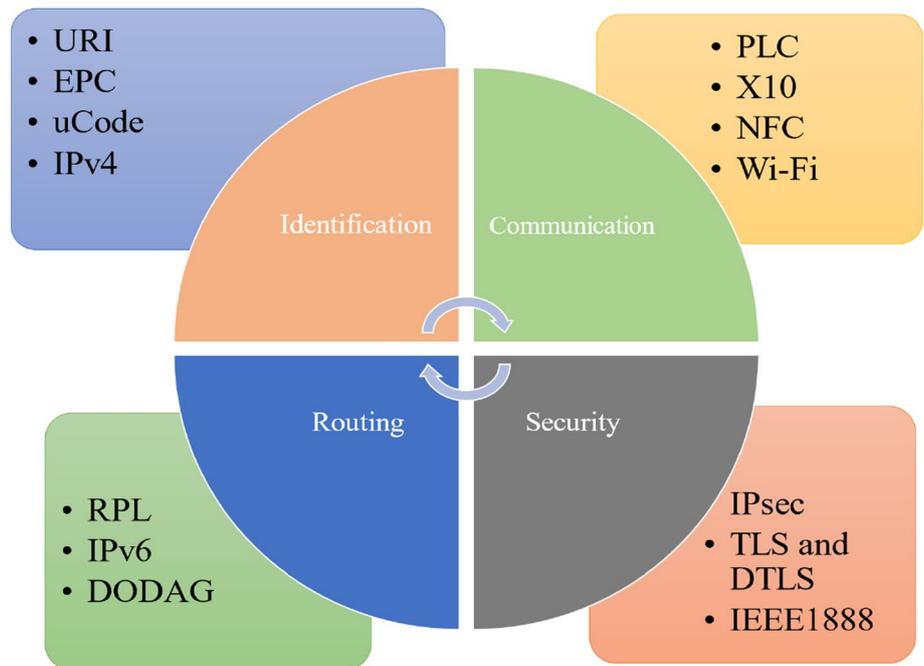
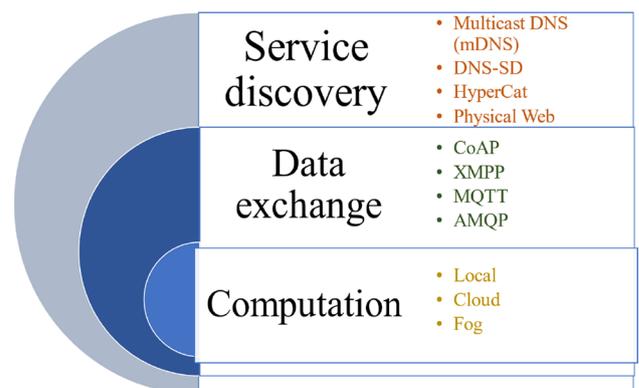**Fig. 2** Symmetric diagram of sensor networks

Fig. 3 Type of perception layer technology
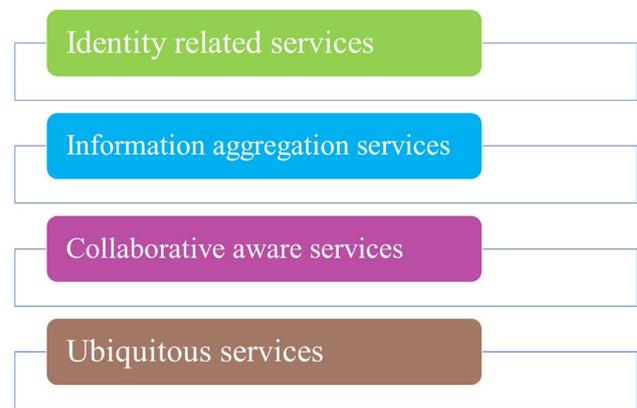

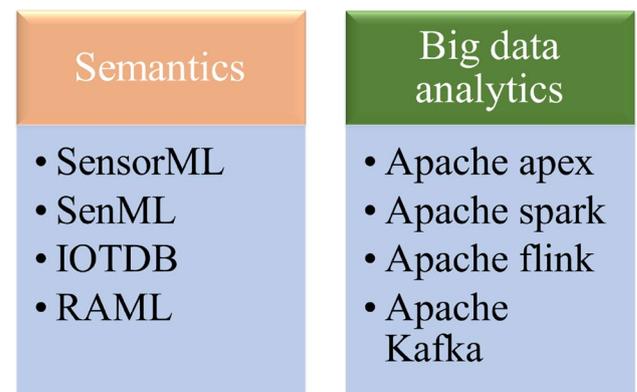**Fig. 4** Network layer technology

Fig. 5 Middleware Technologies

Fig. 6 Type of application layer technology

Fig. 7 Categories of business layer technology

and requested based on names and addresses [21]. Additionally, this layer makes decisions, processes incoming data, and provides necessary services. Figure 5 shows middleware technologies.

Application layer technologies: This layer is responsible for providing requested services to IoT users via a simple interface without knowing how service requests are processed in the underlying layers. IoT users can access a service (e.g., reading or setting temperature conditions remotely or tracking and managing vehicles) using many platforms (e.g., laptops, smartphones, and smartwatches) via web portals or applications [22]. Services vary based on the IoT scenario but can be categorized into four main classes as described in Fig. 6.

Business layer technologies: In this layer, unlike the application layer, service data and IoT environmental data, such as business models, flowcharts, and graphs, can be accessed. This access helps administrators in the design, analysis, implementation, evaluation, monitoring, and development of IoT systems because the output of each of the previously mentioned layers is analyzed in this layer to improve services and protect user privacy [23]. The technologies in this layer can be divided into two categories based on their functions (i.e., semantics and Big Data analytics) as described in Fig. 7.

3.2 Communication protocols and IoT platforms

Efficient communication between IoT devices and the internet is at the heart of how any IoT system works. IoT communication relies on a variety of platforms and protocols to ensure seamless connectivity, working together and efficient information exchange of protocols for IoT communication [24].

- **MQTT (Message queuing telemetry transport)** MQTT is a short messaging protocol designed for low-bandwidth and high-latency networks. It uses a publish/subscribe model to ensure efficient communication between devices and servers. MQTT is widely used in applications such as remote monitoring, smart homes, and industrial automationbecause of its simplicity and low cost.

- **CoAP (Constrained application protocol**) CoAP is designed for constrained devices and networks. It enables effective communication in resource-constrained environments, use the client–server model and is often applied to intelligent networks, health care and environmental inspection.
- **HTTP/HTTPS (Hyper text transfer protocol)** Secure versions of HTTP and HTTPS are often used for IoT applications that require standard web communications. Although it is not as lightweight as MQTT or CoAP, it is suitable for applications with sufficient bandwidth.
- **AMQP (Advanced message queuing protocol)** AMQP is a robust protocol designed for message-focused middleware. It helps to ensure reliable communication which makes it suitable for applications that require high reliability, such as financial systems or industrial automation.
- **LoRaWan (Long Range Wide Area Network)** LoRa WAN is a low-power, long-life protocol. It is ideal for connecting IoT devices in remote locations. They are generally used in smart agriculture, environmental monitoring and city infrastructure [25, 26].

4 Applications in process monitoring and control

4.1 Manufacturing and industry 4.0

The Fourth Industrial Revolution, or Industry 4.0, is a manufacturing paradigm shift that is defined by the incorporation of automation, smart systems, and digital technology into conventional industrial processes. Innovations in big data analytics, cloud computing, sensor networks, Internet of Things, and artificial intelligence (AI) are driving this shift. With the use of these technologies, manufacturers can increase output, boost productivity and design more adaptable and responsive production processes [7].

    Sensor networks play a crucial role in Industry 4.0 by providing real-time data collection and monitoring capabilities. Within a smart factory, sensors are integrated into devices, machinery, and merchandise to continually track and monitor a range of factors, including vibration, temperature, pressure, and energy usage. After that, this data is sent via wireless networks to cloud-based platforms or centralized control systems for analysis [27]. By utilizing this data, manufacturers may uncover information about how well their machinery is operating, anticipate maintenance requirements and spot possible problems before they result in expensive downtime.

    IoT integration is another key aspect of Industry 4.0, enabling seamless communication between machines, systems, and humans. IoT devices gather and share data in industrial situations which helps with automated decision-making and production line optimization. For instance, IoT-enabled predictive maintenance systems use sensor data to predict when equipment is likely to break, enabling prompt maintenance that causes the least amount of inconvenience [28]. Another benefit of IoT is the deployment of smart supply chains, which manage inventory levels, demand projections and logistics in real-time to improve operational efficiency and cut waste.
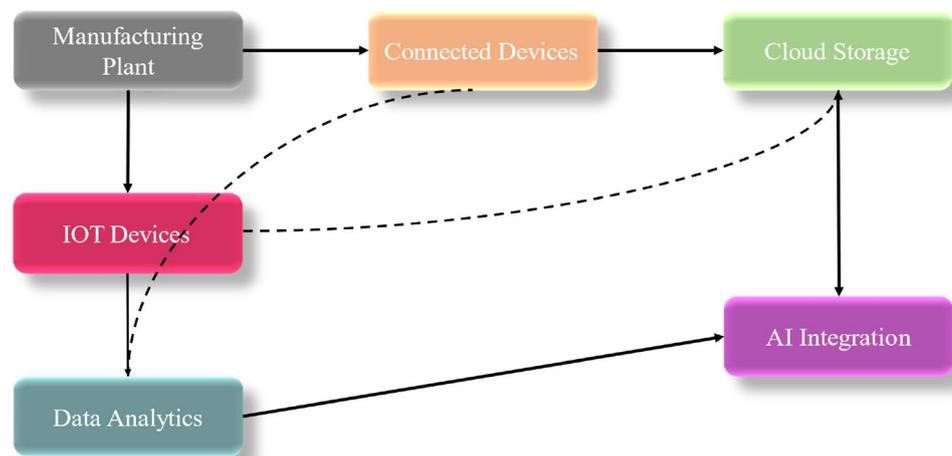
    Automation and robotics are central to Industry 4.0, allowing manufacturers to achieve higher levels of productivity and precision. Advanced robotics are used to handle hazardous chemicals, automate monotonous jobs, and accurately complete complex assembly procedures. They are frequently outfitted with sensors and artificial intelligence [29]. These robots can collaborate with human operators on the factory floor, enhancing flexibility and productivity. Automation also includes manufacturing procedures like 3D printing, which converts digital drawings into tangible goods instantly, allowing for mass customization and shortening the time it takes to launch new products.

    Big data analytics is essential for making sense of the vast amounts of data generated by sensor networks and IoT devices in Industry 4.0 environments. By utilizing sophisticated analytics and machine learning algorithms on this data, manufacturers can identify trends, streamline workflows, and make informed decisions. Big data analytics, for example, can be used to improve quality control by instantly revealing flaws and enabling corrective action [30]. Analyzing production data to pinpoint problem areas and bottlenecks, also aids in process optimization.

    Cloud computing provides the infrastructure needed to store, process, and analyze the data generated by Industry 4.0 technologies. Cloud platforms provide strong computational resources and scalable storage options that can manage the intricate analytics needed for Industry 4.0 applications like supply chain optimization and predictive maintenance [31]. Cloud-based solutions also make it possible to remotely monitor and control manufacturing processes, allowing managers to supervise several production sites from one central location.

    Cybersecurity is a critical consideration in Industry 4.0, as increased connectivity and reliance on digital technologies introduce new vulnerabilities. Producers must implement strong cybersecurity measures to guard their systems, data,

Fig. 8 Manufacturing and industry 4.0 connectivity

and networks against online attacks [32]. This entails protecting Internet of Things devices, encrypting data transfers, and ensuring that sensitive data is only accessible to those who are allowed. Figure 8 explains interconnection of manufacturing and industry 4.0.

4.2 Smart agriculture

Sensor networks and similar technologies have revolutionized modern agriculture, opening the door for "smart farming" and "precision agriculture." Farmers can now maximize resource utilization, improve agricultural yields, lessen their impact on the environment, and operate more efficiently overall thanks to these advancements. Farmers may use data-driven decisions to enhance agricultural practices by combining sensors, Internet of Things (IoT) devices, data analytics, and automated processes [33].

Precision agriculture is the art and science of increasing crop productivity through the application of cutting-edge technologies. Precision agriculture is developing mostly due to wireless sensor network (WSN) technologies. Recent electronics and wireless communications developments have made it possible to build and produce compact, multi-functional, low-cost, low-power sensors that can communicate over short distances [34]. Numerous low-cost, intelligent sensors that are wirelessly connected and placed in huge quantities offer a plethora of possibilities for home, city, and environmental monitoring and control.

IoT Integration plays a crucial role in smart farming. Sensor networks are used to integrate Internet of Things devices, such as weather stations, drones, and autonomous tractors, to gather massive volumes of data. Large tracts of farmland can be surveyed by drones fitted with cameras and sensors, which can record information on insect infestations, disease prevalence, and plant growth. Farmers can fully see their crops thanks to the combination of this airborne data and sensors at ground level [35]. This allows for timely interventions like fertilizer targeting or pesticide application.

Smart irrigation systems are one of the most impactful applications of sensor networks in agriculture. Smart irrigation systems minimize water waste and enhance crop health by optimizing water usage through the use of soil moisture sensors, weather data, and real-time monitoring. Water management is made more effective and sustainable by these systems, which can automatically modify water levels in response to plant requirements, soil conditions, and predicted weather patterns [36]. This is especially crucial in areas with limited water resources.

Weather and environmental monitoring is critical for agriculture, as weather conditions directly impact crop growth and yields. Meteorological patterns and agricultural operations can be planned using real-time meteorological data from sensor networks which includes temperature, humidity, rainfall, and wind speed. When farmers receive early signs of impending bad weather, such as storms or frost, they can take preventative action like covering crops or rearranging harvest dates. Furthermore, environmental monitoring may monitor soil erosion, water use, and air quality all of which support sustainable agriculture methods [37].

Data analytics and AI are used to process the vast amounts of data generated by sensor networks in agriculture. To produce useful insights, real-time and historical data are analyzed using advanced analytics and machine learning models. AI can assist farmers in making well-informed decisions regarding planting and harvesting by predicting crop

yields based on weather patterns, soil data, and plant health [38]. Data analytics may also lower input costs, maximize resource use, and raise agricultural profitability all around.

Sustainability and resource conservation are major focuses in modern agriculture. Through the utilization of sensor networks and Internet of Things devices, farmers may lower their water, fertilizer, and pesticide usage, resulting in more ecologically friendly farming methods. By applying resources only where and when needed, precision farming techniques minimize waste and lessen the negative effects of agriculture on the environment [39].

4.3 Smart healthcare

By enabling more effective, individualized, and data-driven care through wearable technology, IoT integration and remote monitoring, sensor networks are revolutionizing the healthcare industry. By delivering real-time data, enhancing patient outcomes, and lightening the load on healthcare systems, these technologies are revolutionizing patient care, diagnosis, treatment, and health management [40].

Remote patient monitoring (RPM) is one of the most impactful applications of sensor networks in healthcare. Wearable technology, such as health patches and smartwatches, has sensors built in to continuously monitor vital indications including blood pressure, oxygen saturation, glucose levels, and heart rate. Healthcare professionals can monitor a patient's health even while they're not in a clinical setting because to the transmission of this real-time data. RPM makes it possible to identify health problems early, lower the rate of readmissions to hospitals, and enhance the treatment of chronic illnesses like diabetes, hypertension, and heart problems [41]. Continuous glucose monitors (CGMs), for instance, assist diabetics in controlling their blood sugar levels by sending out alerts when levels are too high or low.

Wearable health devices have become increasingly common, offering patients and healthcare providers valuable insights into daily activities and overall health. In addition to tracking physical activity, fitness trackers like Fitbit, Apple Watch, and others also gather information on sleep habits, caloric intake, and cardiovascular health. Doctors and individuals can use this information to detect health risks and encourage preventive steps. Additionally, by encouraging patients to take a more proactive approach to wellness, these gadgets let patients take greater ownership of their health [42].

Telemedicine and IoT are revolutionizing healthcare delivery, especially in remote and underserved areas. Healthcare providers can perform virtual consultations and real-time patient monitoring with IoT-enabled devices like digital stethoscopes, heart monitors and connected blood pressure monitors. By incorporating IoT into telemedicine, patients can receive timely medical advice and intervention, access to healthcare services is improved, and in-person visits are less necessary [43]. IoT-enabled wound sensors, for instance, can be used by a patient recuperating from surgery to track the healing process. The doctor can evaluate the data automatically.

Smart hospital systems rely on sensor networks to streamline hospital operations and improve patient care. Medical equipment, hospital beds, and wearable devices provided to patients during their stay are all equipped with sensors. These sensors ensure prompt treatments by tracking patient movements, keeping an eye on vital signs, and giving medical professionals access to real-time data. Sensor networks are also used to monitor the availability of medical equipment and supplies which lowers waste and enhances resource management [44]. To reduce human mistakes, smart infusion pumps, for example, employ sensor data to control the dosage of medication given to a patient.

Elderly care and assisted living are areas where sensor networks are making a significant impact. Sensor networks are utilized in assisted living homes and smart houses to keep an eye on senior citizens' health and activities. When motion sensors notice unexpected inactivity or falls, they notify family members or caretakers. Wearable sensors make it possible to monitor vital indicators and identify anomalous patterns, such as rapid variations in blood pressure or irregular heartbeats, which can lead to prompt medical attention [45]. With the use of these technologies, senior citizens can maintain their independence while having ready access to assistance in an emergency.

Real-time diagnostics and personalized medicine are being advanced through the use of sensor networks. For example, biosensors enable real-time health assessments by detecting and tracking biomarkers in physiological fluids like blood or saliva. Without the need for intrusive testing, these sensors offer quick diagnostic capabilities, detecting ailments like infections, cancer signs, or cardiovascular problems. Sensor data can be utilized in personalized medicine to customize therapies according to a patient's unique health profile [46].

Surgical precision and robotics are enhanced by sensor networks. To improve precision during minimally invasive procedures, sensors built into surgical equipment give doctors real-time input on tissue resistance, force, and position. Sensors are used in robotically assisted operations, like the Da Vinci system, to provide precise data that helps surgeons execute intricate procedures with more control and accuracy [47]. These advancements make surgery safer and more effective by lowering recovery times and the possibility of complications.

Chronic disease management is significantly improved through sensor networks. Continuous sensor monitoring gives vital information that enables real-time treatment plan adjustments by healthcare professionals for patients with illnesses like diabetes, asthma or heart disease. For instance, wearable sensors that track vital signs and notify physicians of any aberrant trends can help patients with heart failure avoid hospitalization by enabling early intervention [48]. Patients can take charge of their health with the help of this constant data flow which also keeps medical professionals updated on the patient's state.

Artificial intelligence (AI) and data analytics are integral to processing the vast amounts of data generated by sensor networks. Artificial intelligence (AI) systems examine health data to spot trends and anticipate possible health problems before they arise. Healthcare professionals may act to prevent a heart attack by using machine learning models, which, for instance, can evaluate data from heart rate monitors and forecast the chance of a cardiac event. More individualized treatment plans are also made possible by AI-driven data analytics, which evaluates a person's medical records and recommends solutions that are tailored to their needs [49].

4.4 Smart cities

With the use of sensor networks, IoT, data analytics, and automation, smart buildings and cities are bringing about a revolutionary change in urban design and infrastructure that will increase the liveability, sustainability, and efficiency of urban areas. By providing real-time data on a variety of areas of city life, such as trash management, traffic management, and energy usage, sensor networks are essential to the development of smart cities [50]. With the aid of these technologies, city officials, planners, and citizens may make well-informed decisions that enhance quality of life, lower expenses, and provide better services.

Smart cities combines cutting-edge technologies in order to improve the management of urban services and resources and increase their sustainability and resilience to the difficulties posed by growing urbanization [51].

Traffic management is a key area where sensor networks are making an impact in smart cities. Real-time data on traffic flow, vehicle speed, and congestion is collected by sensors that are implanted in roadways, traffic lights, and automobiles. By utilizing this data, traffic signal timings can be optimized, bottlenecks can be decreased, and public transit efficiency can be raised. For instance, smart traffic signals can reduce wait times and fuel usage by modifying their timing in response to the flow of traffic [52]. Furthermore, real-time information on bus and train schedules is provided via GPS-enabled sensors in public transportation systems, enhancing the dependability and ease of public transportation.

Energy efficiency and smart grids are crucial for reducing the environmental footprint of cities. Sensor networks in smart cities keep an eye on energy consumption in a variety of settings including industrial and residential structures as well as commercial buildings. Real-time data on electricity usage from smart meters enables more precise billing and improved demand control. Sensor networks function in tandem with smart grids to optimize the integration of renewable energy sources like solar and wind power and to enable dynamic balancing of energy supply and demand [53]. Smart grids can modify energy distribution in response to peak demand periods, thereby averting overloads and guaranteeing a more consistent energy supply.

Waste management in smart cities is enhanced by the use of sensors that monitor waste levels in bins and dumpsters. Through communication between these sensors and waste collecting systems, garbage trucks can have their routes and timetables improved, saving money on fuel and operating expenses. Cities can encourage recycling and cut down on landfill usage by gathering statistics on waste creation patterns [55]. Furthermore, hazardous trash and overflowing bins can be detected by smart waste systems, enhancing cleanliness and lowering environmental hazards.

Water management is another critical aspect of smart city infrastructure. Water distribution networks employ sensors to keep an eye on water pressure, flow rates, and quality, guaranteeing a reliable and efficient supply of potable water. Real-time leak location and identification via leak detection sensors help to stop water loss and lower repair costs. Stormwater management systems in smart cities employ sensors to track rainfall and manage water release from reservoirs and drainage systems to avoid flooding [54]. These developments lessen the effects of natural calamities like floods and enable cities to manage their water supplies more responsibly.

Public safety and security are significantly enhanced by sensor networks in smart cities. Real-time monitoring of public areas is made possible by IoT devices such as motion detectors and surveillance cameras, which enable emergency services and law enforcement to react to crises more swiftly. When gunshots, motor accidents or fires are detected, sensors can immediately notify the appropriate authorities so they can respond quickly [56]. Furthermore, motion-sensor-equipped smart lighting systems increase safety by regulating lighting settings in public areas in response to foot traffic, guaranteeing well-lit surroundings without consuming energy.

Environmental monitoring is a vital function of sensor networks in smart cities. Numerous sensors are positioned all around the city to monitor temperature, humidity, noise pollution, and air quality. This data is crucial for regulating urban ecosystems. For instance, air quality sensors assist lessen exposure to hazardous situations by detecting harmful pollutants and giving city officials and citizens real-time updates. In order to lessen air pollution, regulations that restrict industrial emissions or encourage the use of public transportation can be put into place using the data from these sensors [57]. By keeping track of heatwaves, floods, and other extreme weather occurrences, environmental monitoring contributes to climate resilience by assisting cities in adapting to the effects of climate change.

4.5 Smart buildings

Sensor networks allow automated systems to optimize energy use, improve security, and raise tenant comfort and well-being in smart buildings. Smart buildings are crucial for the creation of smart cities because they enhance urban living conditions, resource management, and overall energy efficiency. One essential component of smart buildings is energy management. To ensure energy is used effectively, sensors keep an eye on the lighting and HVAC (heating, ventilation, and air conditioning) systems. By adjusting lighting levels based on occupancy and the availability of natural light, smart lighting systems use motion and daylight sensors to save energy. Sensor-equipped HVAC systems optimize comfort while consuming the least energy by adjusting the temperature and ventilation in a space according to the number of inhabitants. Furthermore, real-time tracking of energy consumption by smart meters allows building managers to spot inefficiencies and cut expenses related to operations [58].

Smart building architecture is centered on Building Automation Systems (BAS). BAS uses sensor networks to regulate HVAC, lighting, security, and access control, among other building operations. By utilizing real-time data from sensors, these systems make automatic adjustments to settings that enhance building operations efficiency. For instance, automated blinds can react to sunlight levels to lower cooling loads, and smart thermostats can learn user preferences and change temperatures accordingly. In addition to increasing energy efficiency, BAS also improves building occupant comfort and convenience [59]. Smart buildings prioritize the comfort and well-being of their occupants by using sensors to track the quality of the indoor environment. Sensors keep an eye on things like temperature, humidity, noise levels, and air quality to maintain a comfortable and healthy home environment. For example, carbon dioxide (CO_2) sensors can determine when ventilation is necessary to maintain a high level of air quality and noise sensors can pinpoint locations that might need soundproofing [60]. In addition, customized lighting and HVAC settings that enhance occupant happiness and productivity can be created in smart buildings based on specific preferences.

IoT devices and sensor networks improve security and access control in smart buildings. Doors, windows, and security cameras all have sensors that track and identify unwanted entry into the building. By eliminating the need for conventional keys or access cards and allowing admittance to only authorized individuals via biometric data (such as fingerprints or face recognition), smart access control systems increase security. Furthermore, in the event of an emergency, such as a break-in or fire, building management or security staff receive real-time alerts from smart alarms and surveillance systems [61]. Smart buildings lessen their environmental effect by employing sensor networks to track waste production, energy use, and water usage. For instance, by modifying plumbing and irrigation systems in response to occupancy and meteorological conditions, smart water systems save water consumption and identify leaks. In order to lessen their need for non-renewable resources, smart buildings can incorporate renewable energy sources like solar panels and employ energy storage technologies [62]. Table 2 illustrates different other work and their pros and cons.

Table 2 Classification table of related work

Study	Focus area	Methodology	Pros	Cons
Sheng et al. (2020)	Industrial IoT	Multi-layer architecture	High reliability, scalability	Energy efficiency not addressed
Jaladi et al. (2021)	Environmental monitoring	LoRaWAN-based sensor nodes	Energy-efficient design	Limited scalability
Devan et al. (2022)	Healthcare IoT	CoAP and cloud analytics	Real-time monitoring	Privacy concerns
Rajput and Kumaravelu (2023)	Precision agriculture	Fuzzy decision-making system	Sustainability-focused	High initial cost

5 Challenges and limitations

5.1 Scalability and interoperability

Ensuring interoperability across heterogeneous devices and systems gets more difficult as IoT and sensor networks grow. Devices from different suppliers are challenging to integrate because different manufacturers frequently employ proprietary protocols. Furthermore, resilient infrastructure that can manage increased data flow without sacrificing speed is needed for scaling up sensor networks [63].

5.2 Energy efficiency

Energy efficiency is one of the main issues with sensor network deployment, particularly in isolated or difficult-to-reach places. Sensor nodes frequently run on batteries, which can make battery replacement difficult or expensive. Consequently, maximizing power consumption is essential to extending the network's life. To solve this problem, strategies like energy harvesting, low-power communication protocols and sleep scheduling are being investigated [64].
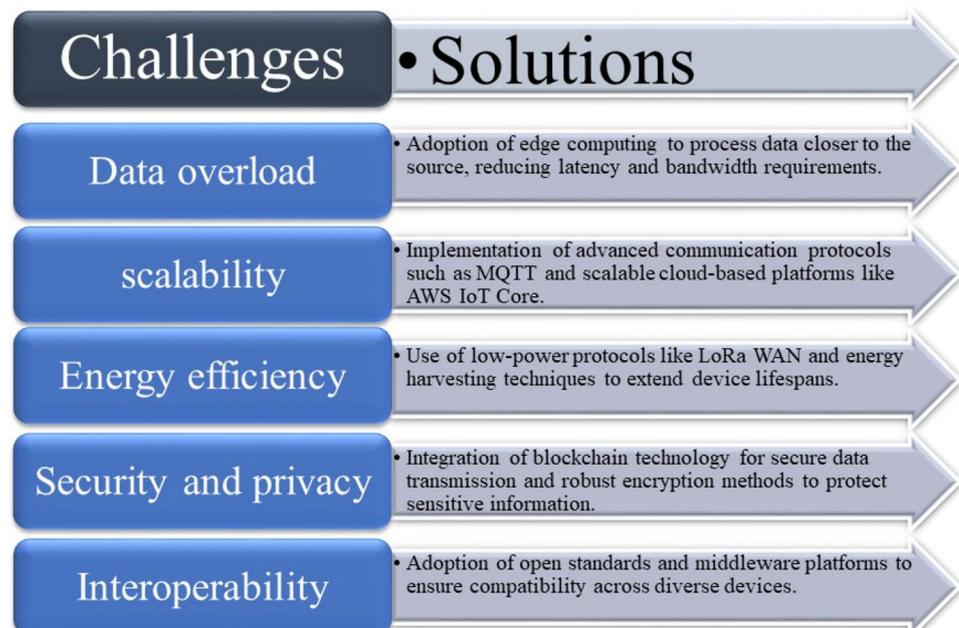
5.3 Security and privacy concerns

IoT and sensor networks are susceptible to a range of security risks, such as unapproved access, data breaches, and cyberattacks. IoT devices are vulnerable to attacks that could jeopardize the security of control systems and the integrity of data since they frequently function in unprotected contexts. Addressing these issues requires ensuring secure communication, data encryption, and access management. Sensitive personal or corporate data sent over IoT networks also gives rise to privacy concerns [65].

5.4 Data management

The vast amount of data produced by Internet of Things devices presents analytics, processing, and storage difficulties. Real-time data streams may be too large for traditional data processing methods, necessitating more sophisticated data management and analytics tools. Furthermore, complex algorithms and techniques like AI and machine learning are needed to derive valuable insights from IoT data [14]. Figure 9 explains various challenges and solutions of the IoT-sensor networks.

Fig. 9 Various challenges and solutions of sensor network

6 Future directions and emerging trends

6.1 5G and beyond

It is anticipated that the introduction of 5G networks will greatly expand the possibilities of sensor networks and the Internet of Things by offering greater connectivity, reduced latency, and faster data rates. More sophisticated uses of process monitoring and control will be made possible by this, including large-scale sensor installations in smart cities, autonomous cars in manufacturing, and real-time video streaming from faraway places [66].

6.2 AI and machine learning integration

Process control is projected to transform thanks to a major trend: incorporating AI and machine learning into the Internet of Things platforms. Artificial Intelligence (AI) can detect patterns, anticipate equipment malfunctions and enhance procedures instantly by examining vast amounts of data from Internet of Things devices. Anomalies in sensor data can be found using machine learning methods [67].

7 Discussion and summary

We have seen from the study that Smart IoT and sensor networks provide real-time monitoring, data-informed decision-making and automation across urban environments, healthcare, and industrial sectors. These technologies facilitate interconnected systems and optimize operations by enhancing efficiency, predictive maintenance, and sustainability. The study indicates that system integration and data management necessitate collaborative solutions.

8 Key points of study

- ML/AI-driven predictive maintenance decreases downtime and prolongs asset lifespan in manufacturing, transportation, and utilities.
- Smart cities can employ IoT for transportation, energy management, trash management, and public safety.
- Sensor networks can facilitate sustainable urban growth by decreasing energy consumption, enhancing air quality, and augmenting citizen safety.
- IoT-enabled wearables and telemedicine systems can improve patient outcomes and decrease healthcare expenses.
- Artificial intelligence in Internet of Things healthcare systems can also facilitates early diagnosis and tailored therapy.

9 Primary concerns

- IoT devices introduce novel vulnerabilities for cybercriminals, heightening dangers to data security and privacy.
- Inconsistent IoT protocols impede system interoperability and scalability.
- Energy consumption is a significant issue for power-intensive IoT devices. Numerous IoT gadgets are powered by batteries, necessitating maintenance and raising environmental concerns.

10 Future implication of study

- Undertake research to formulate global standards for IoT connectivity, data management, and device integration. There is a necessity for modular, scalable, and secure IoT architectures. Subsequent research should concentrate on establishing universal standards for device integration across many platforms and domains.

- Subsequent study should concentrate on low-power IoT devices, energy-harvesting networks, and AI-facilitated energy optimization. Investigation is required on energy-harvesting devices, low-power sensors, and effective communication protocols to optimize energy conservation.
- Subsequent research must concentrate on privacy-preserving artificial intelligence and blockchain technologies to protect sensitive information andinvestigate privacy-preserving machine learning methodologies to safeguard sensitive information while maintaining analytical integrity.
- Investigation into sophisticated AI algorithms for the real-time analysis of IoT datasets to facilitate autonomous decision-making and self-optimization and create adaptable IoT architectures for safe data transmission, cross-platform compatibility, and scalability.
- Explore IoT solutions for intelligent transportation, renewable energy, and sustainable urban development and investigate IoT-enabled supply chain management systems that enhance efficiency, traceability, and sustainability.

11 Conclusion

IoT and sensor networks are enabling real-time monitoring, automation, and data-driven decision making in industry, agriculture, healthcare, and urban development. Sensor networks provide unprecedented visibility into operations, enabling precise process control, efficiency, and early issue discovery. Scaling sensor networks to monitor traffic, energy use, and public safety in real time in smart cities can improve quality of life and sustainability. Predictive maintenance can minimize unexpected equipment failures, optimizes resource use, and ensure maintenance is done when needed, eliminating production or service interruptions. IoT also allows remote patient monitoring, early disease detection, efficient medical device administration and improves energy efficiency, security, and urban sustainability in smart cities and buildings.

Despite these developments, data security, privacy, and standardization remain major issues. IoT adoption is becoming safer and more trustworthy as encryption, blockchain, and worldwide IoT standards improve. Future developments in IoT, sensor technologies, and AI-driven analytics will boost efficiency, sustainability, and innovation across all sectors.

In conclusion, IoT and sensor networks are transforming process marketing and control into smarter, more efficient, data-driven operations. These technologies will enable increased connectedness, better decision-making, and long-term sustainability in a digital environment, shaping the future of industries. In order to effectively manage data and ensure that various systems operate in harmony, it is imperative that we implement solutions that are collaborative. Future research should focus on the development of IoT systems that are both secure and capable of expanding, while simultaneously utilizing power that is not depleted. Additionally, it is imperative to investigate the potential of IoT in the areas of energy management, city planning, and the transportation of products.

Declarations

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