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Industrial Internet of Things: Implementations, challenges, and potential solutions across various industries

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ABSTRACT

The Industrial Internet of Things (IIoT) has emerged as a potent catalyst for transformation across many industries as a part of Industry 4.0. This review thoroughly examines IIoT applications, demonstrating how it enhances operational efficiency, informed decision-making, cost optimization, innovation, and workplace safety. While prior research has often concentrated on technical dimensions such as fog and edge computing, network protocols, or big data integration, several emerging and high-impact application areas remain underexplored. This study addresses that gap by systematically reviewing IIoT implementations in critical yet often overlooked domains, including environmental monitoring, agriculture, construction, healthcare, robotics, smart grids, and predictive maintenance. It offers fresh insights into how IIoT is being adapted to meet real-world challenges in these sectors. In addition to outlining the current landscape, the review identifies core barriers such as data security, interoperability, and system scalability. It underscores the importance of cross-sector collaboration and strategic alignment to fully leverage the transformative potential of IIoT. The paper concludes by outlining key research gaps and future opportunities to guide continued innovation and scholarly investigation.

1. Introduction

The Internet of Things (IoT) is a widespread technological concept that describes ubiquitous Internet connectivity, transforming everyday objects into interconnected devices (Malik et al., 2020; Mayordomo et al., 2011). The idea of the IoT originated in 1999 with an automated detection center at the Massachusetts Institute of Technology based on networks utilizing radiofrequency technology verification (Kim et al., 2020). The primary roles of the constructed system encompass data collection, analysis, transmission, and the execution of information outcomes (Lee et al., 2016). The core principle of the IoT concept revolves around the widespread implementation of a trillion or more intelligent devices. These devices can perceive their surroundings, transmit and analyze the data they gather, and subsequently offer relevant responses to their respective environments (Asha et al., 2022; Talavera et al., 2017; Zhu et al., 2018). The capacity to connect uncommon assets to the Internet would increase society's efficiency and security while enabling effective communication between the digital and physical worlds, a phenomenon known as a Cyber-physical System (CPS) (Ghayvat et al., 2015; Xu et al., 2018). The Industrial IoT (IIoT) is a segment of the IoT that calls for better safety, confidentiality, and networking standards without interfering with actual manufacturing operations because of crucial industrial contexts. Industrial performance is crucial to a country's economic growth, and technological

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Table 1
Comparisons with other review studies published recently about the topics discussed in this review.

Study	Key objective	IIoT applications (No. of sectors)	Comparative analysis of IIoT implications	Research challenges	Potential solutions to mitigate challenges
This study	Explore IIoT implementations, emphasizing their applications in diverse industries, along with associated challenges and potential solutions	√ (12)	√	√	√
Malik et al. (2021)	Discuss the applications of IIoT in eleven different sectors	√ (11)	×	×	×
Qiu et al. (2020)	Analyze the advancements in research related to edge computing within the IIoT.	√ (5)	×	√	√
Pivoto et al. (2021)	Investigate the primary models of cyber-physical system architecture used in an industrial environment	√ (1)	×	×	×
Peter et al. (2023)	Explore the latest manufacturing transformation technologies and the methods that emerging economy manufacturers require to transform	√ (2)	×	√	√
(Gupta et al., 2022)	Provide an in-depth analysis of IIoT use cases in smart manufacturing	√ (1)	×	√	√
Chi et al. (2022)	Examine the latest developments in building knowledge bases for knowledge-based fault diagnosis using ontologies and inductive/ deductive reasoning	√ (1)	×	×	×
Alabadi et al. (2022)	Provide a comprehensive analysis of IIoT and Industry 4.0, specifying the latest developments in these areas and resolving any current shortcomings.	×	×	√	√

√ available; × not available

advancement significantly aids the efficacy of individual organizations and the whole industry. Maintenance planning and efficient supervision of industrial assets and operations are the primary objectives of IIoT (Liu, 2019; Xu et al., 2018). Industry 4.0, on the other hand, is an evolution of the IIoT that prioritizes manufacturing efficiency and safety. The IoT and IIoT domains have advanced significantly, as evidenced by the latest predictions that there will be over 70 billion internet-connected devices by 2025 and that IIoT revenue will exceed 14 trillion dollars in 2023 (Perera et al., 2015).

The IIoT, its developments, and its challenges have been the subject of numerous studies. For instance, Xu et al. (2018) emphasized the architecture of the IIoT, which comprises three distinct layers: the application layer, the communication layer, and the physical layer. A classification of IIoT applications was provided for automation processes. Various networking technologies, including 5 G, machine-to-machine (M2M), software-defined networking (SDN), and deliberated on their applications, were investigated within the context of IIoT. 5 G enhances connectivity and supports a massive number of devices, enabling real-time data transmission crucial for IIoT applications. Meanwhile, M2M facilitates direct communication between devices, streamlining processes and optimizing operations, while SDN offers flexibility and improved security through centralized network management. These technologies significantly enhance connectivity and data transmission capabilities, enabling real-time communication between devices and systems. Their current and future impacts include improved automation, predictive maintenance, and greater flexibility in network management, all of which are essential for optimizing industrial processes and driving innovation in the IIoT landscape. The study also addressed the strategy for resolving wireless IIoT connectivity issues. Alternately, other studies provided a thorough analysis of IIoT from a few distinct viewpoints, such as IIoT-based robotic automation and an emergency response system for fire hazards (Maguluri et al.,

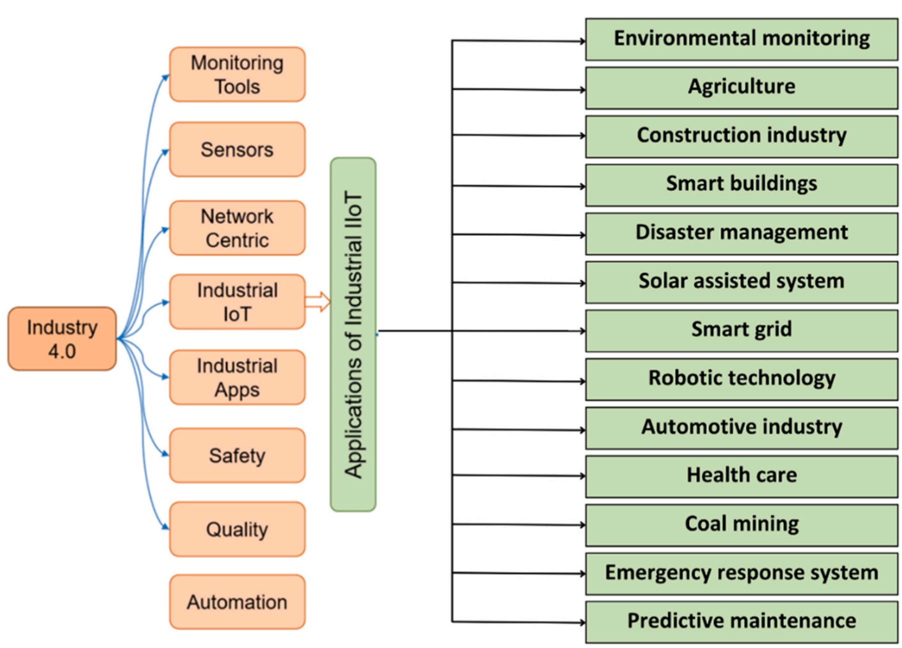

Fig. 1. Main structure of the present review.

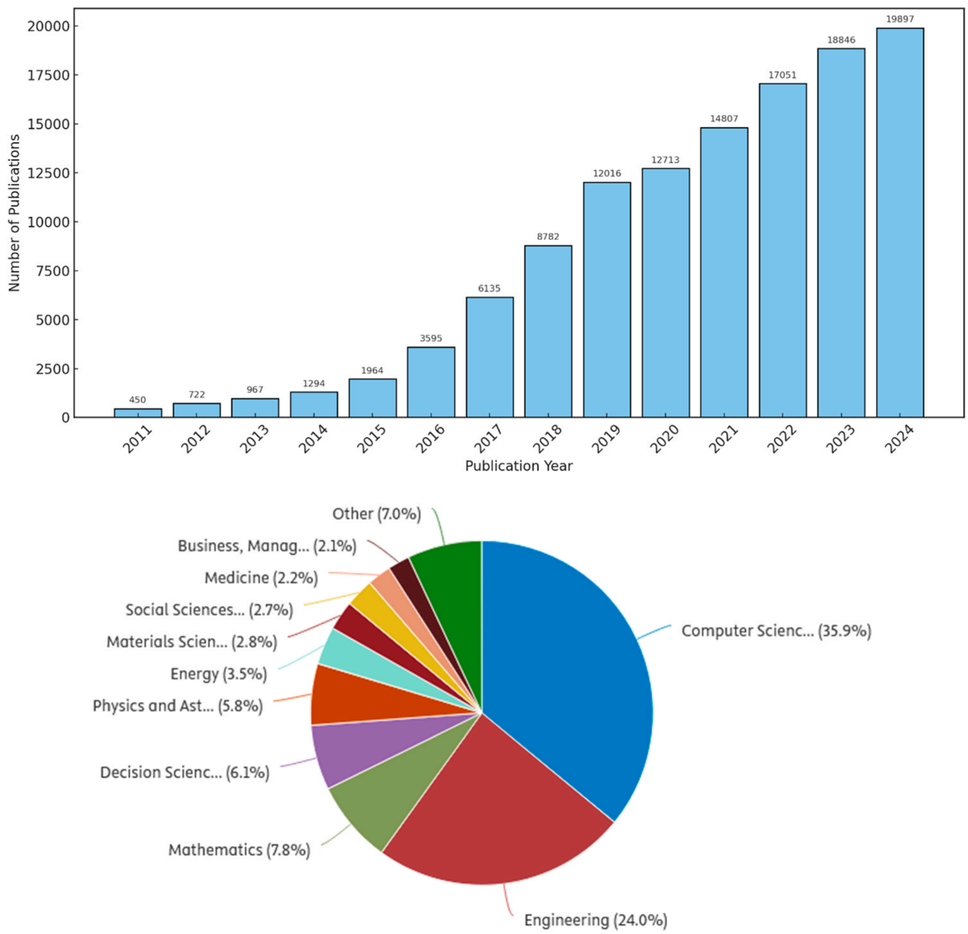

Fig. 2. Publications trends in Industrial IoT during 2011–2024: (a) by year, and (b) by industry.

2018), IIoT data transmission that incorporates energy sources (Kim et al., 2019; Thirumal and Kumar, 2022), implementation activation techniques in IIoT systems featuring edge computing (Aazam et al., 2018; Yang et al., 2020), big data integration with IIoT to generate business insights from industrial data (Al-Gumaei et al., 2018; Alam et al., 2017; Dautov et al., 2019) and identification of changes, prospects, and shortcomings in industry-based IoT solutions may be advantageous for the marketing of IIoT systems (Perera et al., 2015).

The IIoT produces huge amounts of data, and when it is properly analyzed, it can help industries make better decisions and predict future trends. One of the most transformative aspects of digital industrial systems is their ability to interconnect diverse sectors, creating a unified ecosystem where data and insights flow seamlessly. For example, advancements in predictive maintenance from manufacturing can be adapted to healthcare equipment management, while real-time monitoring solutions used in energy grids can inform logistics and transportation. Such cross-pollination fosters innovation and accelerates the adoption of best practices. This review highlights these inter-industry connections, stressing the importance of a collaborative framework that allows technology providers, industries, and policymakers to jointly shape a resilient and intelligent industrial future. Industries are eager to harness this data for better forecasting, maintenance, and risk management, but existing reviews lack the depth needed to guide effective implementation. Despite the expanding literature on IIoT, key challenges like security, interoperability, scalability, and costs continue to obstruct its widespread adoption. This highlights a gap between the theoretical progress and the practical, large-scale use of IIoT. A comprehensive review is needed to bridge this gap, offering guidance to industries facing these challenges and providing researchers with a complete understanding of its potential and limitations. Consequently, this paper sheds light on and critically evaluates the multifaceted utilization of IIoT in several key sectors. These sectors encompass environmental monitoring, construction, agriculture, disaster management, smart buildings, solar-assisted systems, robotics, smart grids, automotive, healthcare, coal mining, emergency response systems, and predictive maintenance. The primary objective is to furnish actionable insights for industry professionals looking to adopt IIoT solutions and researchers focused on identifying novel initiatives for IIoT implementation. This review also offers a comprehensive viewpoint by outlining the advantages and the issues related to IIoT implementation in industrial contexts. Additionally, it functions as a clear framework for fostering preparedness, timely decision-making, and strategic direction, ultimately leading to improved operational efficiency, heightened productivity, and cost optimization. Related to the focus of the present review, Table 1 summarizes and compares the subjects discussed in recent reviews of IoMT.

The present work is organized according to the structure illustrated in Fig. 1. To facilitate a comprehensive discussion, it is organized as follows: Section 2 represents the literature review methodology of this work. Section 3 explores the rise of Industry 4.0 and its significance in society. The applications of IIoT across various disciplines are investigated in Section 4. Section 5 delves into the comparative analysis of IIoT in several domains, along with their advantages and challenges. Section 6 addresses several challenges IIoT faces and potential solutions for future research. Finally, in Section 7, the paper concludes by summarizing the overall discussion on the wide-ranging applications of IIoT.

Table 2
Criteria for excluding and including articles in the current study.

Inclusion	Exclusion
▪ The articles published in peer-reviewed academic journals ▪ The articles selected should be relevant to the field of study ▪ The articles should be of high enough quality that they provide actual answers to the topics posed in the research ▪ Grey literature, or any other supplementary sources of information deemed beneficial, is also researched	▪ Even if a publication is academic or peer-reviewed, it will not be considered if the discussion part is inadequate ▪ Any work that doesn't include information about the aforementioned key terms is excluded ▪ The results of any grey literature that appears to be repetitive ▪ Weakly contextualized or referenced "grey literature" must be eliminated

2. Methodology

This study employs a comprehensive literature review methodology to investigate Industrial IoT by focusing on its applications, advantages, challenges, and future opportunities. During this process, peer-reviewed and relevant papers from reputable journals and conferences were selected, thoroughly examined, and critically analyzed. The authors performed database searches utilizing reputable online resources such as Scopus and Google Scholar, in addition to esteemed academic publishers including Nature, Elsevier, IEEE, Wiley, Taylor & Francis, ACS, SAGE, Inderscience, Springer, Frontiers, and MDPI. A diverse range of keywords, including "Industrial Internet of Things", "Industrial IoT", "IIoT", "Applications of Industrial IoT", "Advantages of Industrial IoT", "Benefits of Industrial IoT", "Challenges of Industrial IoT", and "Disadvantages of Industrial IoT," were employed in the search for relevant articles. In recent years, there has been a significant increase in interest and progress in Industrial IoT, as depicted in Fig. 2, across various academic disciplines.

The references and bibliographies of the works discussed above were gathered and organized to comprehensively search for additional relevant literature. The abstracts, introductions, and conclusions of the selected papers were thoroughly examined, and a classification was performed using the following criteria:

(i) Initially, publications from reputable publishers and websites that are only peer-reviewed were taken into consideration.
(ii) Papers authored by scientists in the field were gathered.
(iii) The collected papers were carefully curated to maintain a suitable equilibrium between previous and present studies.
(iv) The analysis included commercial websites that utilized the specified keywords.
(v) The study considered contemporary technologies pertinent to the research.
(vi) Relevant articles referenced in recent scholarly works were obtained, and a comprehensive assessment was conducted on the primary sources utilized in those studies.

A number of questions arose regarding the recent works during the present study. To address these inquiries and enhance the overall caliber of the review, additional readings and literature searches were undertaken. During the process of conducting a comprehensive literature search, we have successfully identified several pivotal phrases that will greatly contribute to substantiating and bolstering our underlying justification. The investigation was facilitated by selecting keywords, including "Industry 4.0", "Cloud computing", "IIoT", "Internet of Things", "Edge computing", "Big data analytics", and "Fog computing". As the investigation progressed, the list of keywords was gradually refined. The inclusion and exclusion criteria for selecting papers in this study are outlined in Table 2.

Although the exclusion criteria provided a solid basis for identifying reliable, peer-reviewed academic publications, some of its qualities looked at bias and judgment. The authors used a test-retest cycle to fix this issue. After picking primary studies at random, three extraction methods were carried out. The extracted data was meant to have a high level of consistency.

3. Industry 4.0 and the industrial revolution

The global industrial environment has significantly transformed in recent years due to ongoing technological improvements, inventions, and developments. Considered to have contributed to three of the earliest phases of industrialization (Lukač, 2015), the integration of mass labor and electricity, the implementation of mechanical production reliant on water and steam power, and the deployment of electronic, automated manufacturing are all regarded as having played a role. The concept of the purported fourth industrial revolution, also known as Industry 4.0, originated in 2011 to advance the German economy (Hermann et al., 2016). To increase industry efficiency,

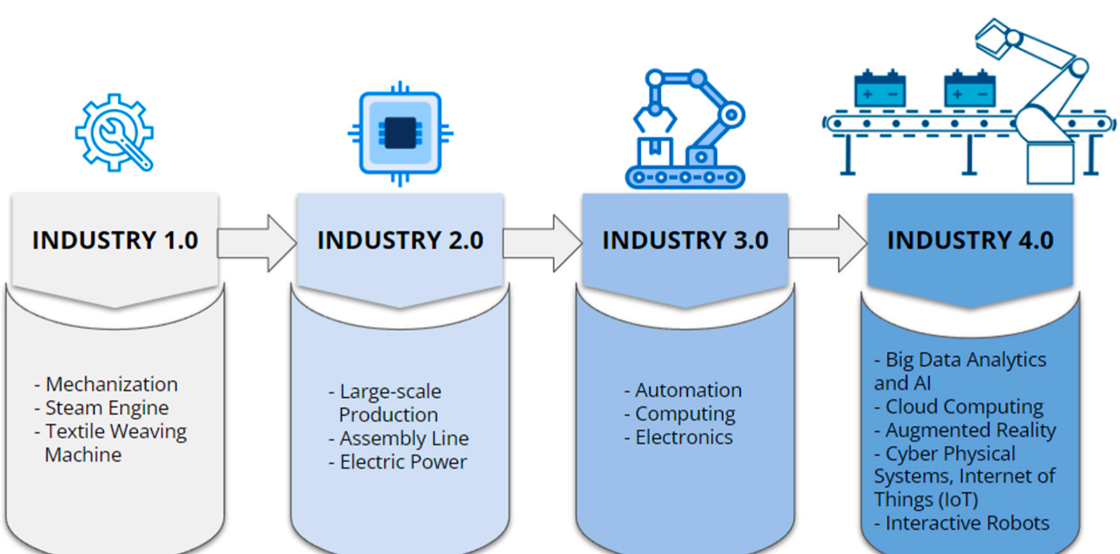

Fig. 3. Industry 4.0 and the industrial revolution.

profitability, security, and transparency, this technological change emphasizes the deployment of CPS, which can communicate with one another and make independent, self-sufficient decisions. Industry 4.0 and the industrial revolution are illustrated in Fig. 3.

Industry 4.0 has been characterized by Wee et al. (Wee et al., 2015) as the digital transformation of the industrial sector, with built-in sensors in almost all products, production machinery, pervasive cyber-physical infrastructure, and analysis of any pertinent information. Additionally, Industry 4.0 incorporates the advantages of existing sectors with cutting-edge technology, resulting in exceptional products that could be utilized in operations that merge technological and physical assets (Schmidt et al., 2015). According to Geissbauer et al. (Geissbauer et al., 2016), Industry 4.0 significantly emphasizes the complete automation of all physical assets and their integration with digital spaces, allowing them to efficiently produce, determine, and transport data.

Industry 4.0 is intended to strengthen and expand current manufacturing operations procedures, regulate and vital systems, as well as advance to a sophisticated level by installing breakthroughs such as IoT, Internet of Services (IoS), self-driving adaptable CPSs, and interactive robotics, models that use accurate data and correspond to practical applications (Lasi et al., 2014). By increasing consumer and marketplace requirements, it also attempts to address the challenging opposition of modern businesses and the rapidly transforming global market. Implementing modern technologies and systems through automated production will pave the way for modern industry and economic development by asserting that an ecosystem of interconnected business operations, companies, and corporations will emerge due to horizontal and vertical integration between systems (Lee et al., 2015).

4. Wide-ranging applications of industrial IoT

IoT is a novel, emerging technology with potential in nearly every industry. With the latest developments of smart cities and expansive environments, which can enhance the quality of their citizens' lives, research into IoT techniques has become more pertinent than ever for these novel scenarios in globalized portals. By integrating heterogeneous devices and compatible technologies (e.g., radio frequency identification (RFID), global positioning system (GPS), sensors, actuator networks, and wireless sensor network (WSN)) that are qualified for tracking, monitoring, identifying, associating, and conversing with things (G, L. et al., 2020; Hadipour et al., 2020; Zhang et al., 2018), IoT provides a promising key for monitoring systems and correlated activities (Zhang et al., 2016). The application of IIoT covers construction industries, environmental monitoring, smart buildings, agriculture, solar-assisted systems, disaster management, robotics technology, smart grids, automotive sectors, emergency response systems, and health care. While distinct, the targeted industries share critical interconnections that underscore the transformative impact of IIoT across various sectors. For example, real-time environmental monitoring is essential for optimizing agricultural practices and strengthening disaster management. Similarly, smart grid innovations enhance energy efficiency in smart buildings, while advancements in robotic technology, particularly in the construction industry, improve safety and operational efficiency, which can be crucial for emergency response systems. These overlaps demonstrate that IIoT is not just a technology applied to individual industries but a foundational framework that drives cross-sectoral synergy. By enabling real-time monitoring, predictive analytics, and automation, IIoT helps diverse industries achieve common goals of efficiency, sustainability, and enhanced performance, creating a unified approach to tackling shared challenges.

4.1. Environmental monitoring

As the effects of global warming continue to worsen, environmental monitoring has emerged as a promising new field of study. However, recently developed climate monitoring procedures are expensive and challenging to implement, frequently needing substantial infrastructure, resources, and expertise (Okafor et al., 2020). Environmental monitoring has entered a new era due to the availability of sensor networks and IoT developments, making it easier to collect high-resolution spatiotemporal information and bridge data gaps in existing datasets (Bublitz et al., 2019; Talavera et al., 2017). For instance, Cavalera et al. (2019) presented a smart aid system for danger and fire situations based on the IoT technology project for fire prevention. This environmental tracking system operates around the clock to observe and regulate multiple environmental variables using specialized smart boxes placed in each space. The system utilizes an effective cloud-based software platform to manage requests from several devices. Six environmental sensors, linked by smart boxes, verify the presence of carbon monoxide, smoke (passive infrared sensor), humidity, and temperature, and detect whether the area has been set on fire. It transmits information to the cloud to be retained, filtered, evaluated, and observed via a mobile app. Further, the authors are developing infrastructure leveraging open-source protocols to control data transactions across IoT devices and the core cloud platform, applying industry-standard protocols, including message queuing telemetry transport (MQTT) and representational state transfer (REST), to suppress common risks in this field.

Jhansi Rani et al. (2020) proposed an autonomous robot system to register environmental standards, including temperature, sky pressure, moisture, and toxic gases. The robot can save documents on the ThingSpeak IoT system and uses GPS coordinates. The mobile robot is controlled by running an Android-based application. The system is built utilizing a cost-effective (<80 USD) ARM-based integrated system, Arduino, and Raspberry Pi linked through a wireless network. The significant benefits are the intuitive app design and the flexibility to act independently after getting instructions from the user. The outcome reveals that it sends updates every 15 seconds to the IoT server for sensor documentation. Renewable energy sources and growth connection procedures for wilderness areas are just two of the numerous areas for future research. Besides, the technique may be easily integrated into contemporary drone technology to make it more appealing.

Global warming has increased concern about the ocean's ecosystem in recent years. Over the last two decades, many maritime environment monitoring systems have been developed using advanced information and communication technologies. Quantitative mapping of anthropogenic activities and oceanic fluctuations is required to design policies, mitigation measures, and trade-offs on a global scale that conserve the planet's largest living area (Duarte, 2014; Shaikh and Hussain, 2019). Marine-Skin, a cutting-edge ultralight environmental monitoring system with advanced detection and logging characteristics, light packaging, and persistence to a depth of 2 km in severely saline Red Sea water, was invented by Shaikh and Hussain (2019). In contrast to invasive bloggers, they devised a wearable jacket made of soft polymers and successfully tested the feather-light gadget on seabream (<0.5 g in air, 3 g including jacket), common goldfish, and wobbegong sharks. It shows how a practical attachment can be used on various species of varying sizes without interfering with the tagged animals' normal behavior.

One of the supreme global issues of this era is air pollution. Current monitoring techniques involve imprecise and insensitive laboratory analysis. Dhingra et al. (2019) suggested a three-phase monitoring system for air pollution as a solution to the issues with current methods. An IoT kit was created using Arduino, gas sensors, and a Wi-Fi module. The kit can be installed in different cities to track pollution intensity. They also made the IoT-Mobair Android app, enabling users to receive pertinent, cloud-based air quality data. The forecast pollution level for the entire route is shown to the user, and an alert is given if the anticipated level is high. The proposed approach is compatible with compact, low-power devices such as sensors, Arduino boards, and Ubidots, despite being more efficient and consuming less energy than conventional pollution monitoring devices. The computational complexity of working with large amounts of sensor data is incredibly challenging. One way would be to use fog rather than cloud computing to reduce

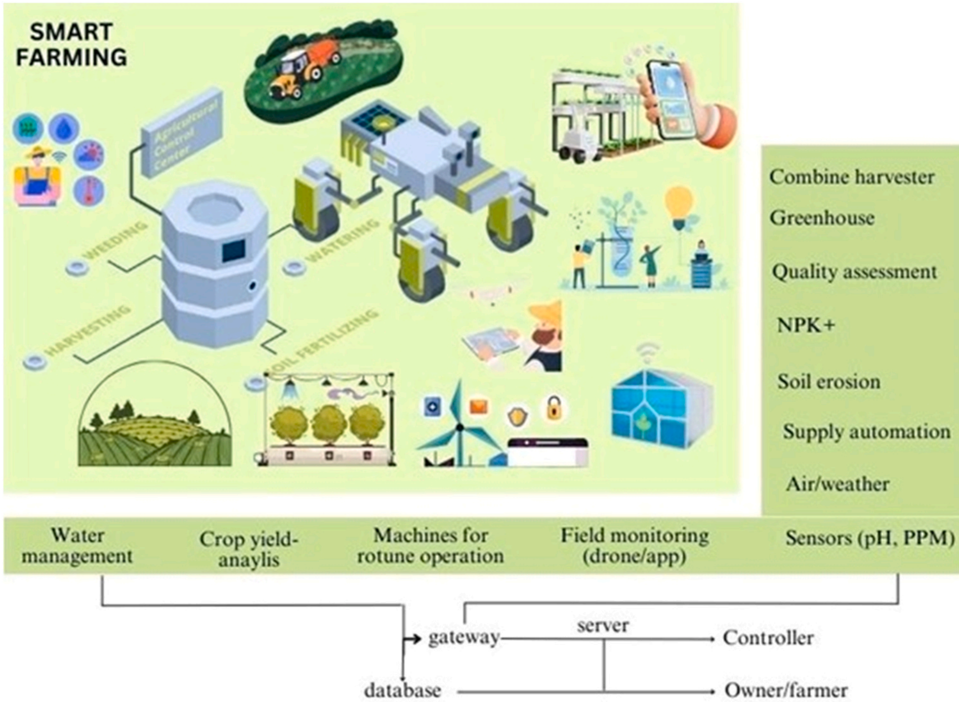

Fig. 4. Smart farming system using IoT.

computational complexity and improve system efficiency.

Asha et al. (2022) developed an IoT-facilitated environmental toxicology system to monitor air pollution by operating the artificial intelligence technique to overcome the shortcomings of conventional monitoring systems and reduce expenses. The sensor array calculates the pollution level and transfers it through gateways to the cloud server for analysis. An artificial algae algorithm (AAA) oriented Elman neural network (ENN) model is applied as a classifier that forecasts future air quality by classifying air contaminants. The AAA was a parameter-tuning tool to dictate the ENN model values optimally. Experimental results demonstrated that the developed model exceeds conventional methods. The model was tested under different conditions that increased the reliability of the project.

4.2. Agriculture

IoT in agriculture is urgently needed because the global population will rise to 9.6 billion by 2050, with a 60 % peak in food demand. The agriculture sector must ensure rapid production to satisfy demand, facilitated by leveraging the latest technologies, particularly IoT, to enable labour-free operations (Acosta-Alba et al., 2019; Akhigbe et al., 2021; Gaspar et al., 2021). IoT is widely involved in agricultural management, monitoring, control, and autonomous machinery systems. Additionally, IoT-based agriculture also utilizes wireless communication technologies, including mobile communication (2 G, 3 G, and 4 G), LoRaWAN (long-range wide area network), ZigBee, Wi-Fi, and Bluetooth (Kim et al., 2020). IoT is used in farm management systems for storage, sales, purchasing, waste management, logistics, monitoring significant inventories, and maintenance, as shown in Fig. 4. Farmers can quickly retrieve all information in one place using a smartphone. Sensors are primarily used to obtain data for determining nitrogen-phosphorus-potassium (NPK) values, disease detection, and soil moisture content. Some of the commercially available smart sensors for agriculture are location sensors (Sequoia), electromagnetic sensors (Crop Canopy Sensor, Clorofilog, OptRx, Veris 3100, CropCycle Phenom, EM-38, and Soil Doctor Systems), optical sensors, and airflow sensors (amplified airflow sensors) (Ratnaparkhi et al., 2020).

Recent agricultural product safety scandals (e.g., lean meat powder pork, dioxin eggs, poisonous bean sprouts, horsemeat, cadmium rice) led to health risks and garnered much public attention. Therefore, enhancing the safety and quality of agricultural goods is a crucial area of research worldwide. It is challenging to promptly surveil an agricultural commodity's standards and safety in all facets by general processing owing to the long experimental phase in laboratories with complex tools and the inability of on-site identification (Ping et al., 2018). However, the appropriate execution of IoT can solve this issue. For instance, Tervonen (2018) outlined a WSN application for the food industry that allows remote environmental monitoring in an industrial storehouse. This study verified that IoT technology can be utilized for farming and food chain operations. Even though this study omitted a real embedded temperature control, observations showed that the storage warehouse's warming capacity needed to be decreased or increased. This implies that several measurement points at various places were necessary for quality control with warmth and other condition monitoring to ensure the desired characteristics for the entire volume. Future studies could exploit the potential of data analysis and an IoT-based network of predictive maintenance for greenhouses that includes an interactive heating, moisture, and illumination control system.

A multi-intelligent control system (MICS) was introduced by Hadipour et al. (2020) to manage water resources in the agricultural industry, motivated by the sharp rise in water scarcity. All water resources in this study were administered using the planned IoT-based system. Three control systems comprise MICS's primary part: a reservoir water level sensor, an alarm control system, and an electro-pump controller. A 4-state switch was built and integrated into the control system for automatic, manual, and IoT-enabled operation, along with an off mode. IoT technology can regulate the entire system, and ringtones or SMS can be used to operate it. According to reports, the technology can save up to 60 % of water and has given a satisfying response to the issue of water management in agriculture. Due to its sturdy and adaptable design, this intelligent system can be used widely in various applications, including agriculture. Significant sums of money and water can be saved using MICS.

Park et al. (2019) designed a wireless sensor node that complements

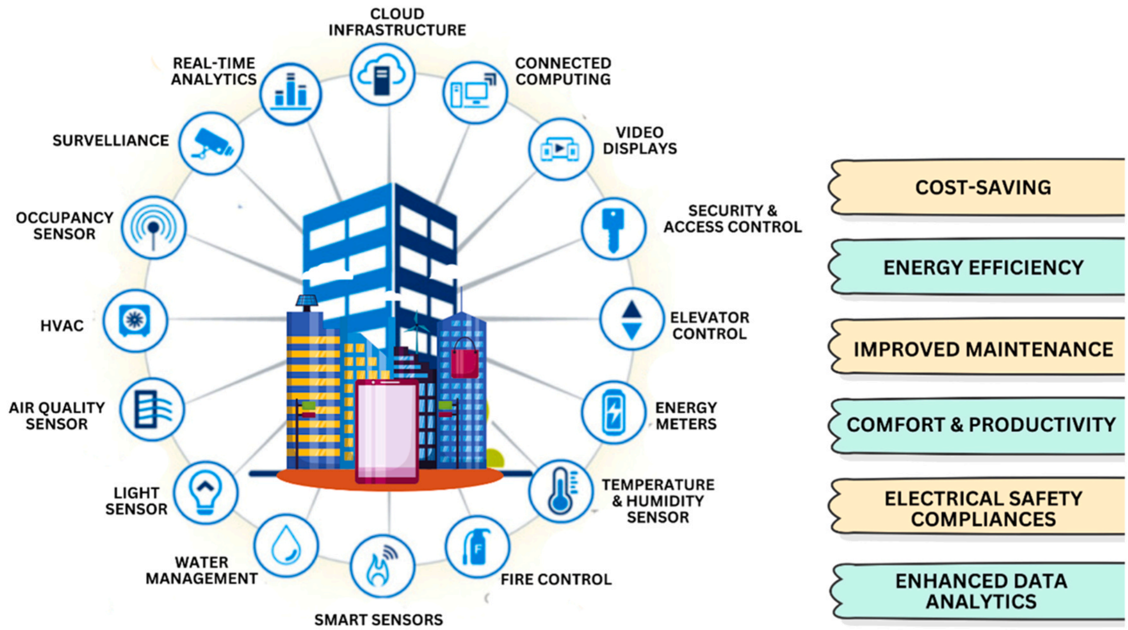

Fig. 5. Smart building infrastructure and associated benefits.

the interface, enabling efficient interaction between the sensor and the controller in a greenhouse. It also assessed the rate of data transmission in proportion to distance. Up to a distance of 25 m, the data rate was 100 % between the wireless sensor node and controller, which were built to interact using Bluetooth. The interoperability of greenhouse control entities can be enhanced using the libgnome library. However, more exploration into the application of long-distance wireless communication (i.e., Zigbee or LoRa) is needed to expand the greenhouse's communication coverage area. G, L. et al. (2020) built an IoT system using light-emitting diodes (LEDs), NPK sensors, and light-dependent resistors (LDRs). By observing and evaluating the soil nutrients, the system guides farmers on the fertilizer needed at set intervals. Python is used to create the software and hardware prototypes for the microcontroller on the Raspberry Pi 3. Fuzzy logic is utilized to determine from sensed data whether there are insufficient nutrients, and the Mamdani inference approach is applied to assess the adequacy of chemical solutions in the tested soil. It is evident from the numerous studies that have been carried out that this established IoT system is helpful for farmers to attain high crop yields.

4.3. Construction industry

Traditional and often physically strenuous construction methods further contribute to the perception of the construction industry as unpleasant and drab, discouraging school dropouts and graduates from entering the profession as experts. These issues can be addressed by utilizing cutting-edge technologies under the aegis of Industry 4.0, the fourth industrial revolution (Han and Golparvar-Fard, 2017; Newman et al., 2021; Oesterreich and Teuteberg, 2016). For example, Li et al. (2018) developed a platform that merges IoT and building information modeling (BIM) technologies so that managers can promptly monitor the cost and progress of construction projects. The design integrates various components into a unified system, including big data, RFID, and cloud computing. This technology has proven its capacity to automate, visualize, and remotely control the complete prestressed structural element procedure. This platform allows stakeholders to monitor their daily activities: decision-making, coordination, and inspection during the prefabrication stage. However, the platform was only intended to gather budget and scheduling information without considering data on productivity and the working environment.

Site supervisors have to scrutinize and take appropriate actions to complete projects safely. Golovina et al. (2016) suggested adopting point cloud-based 4D models for site management and supervision to identify hazards without a physical inspection and recognize workers not wearing required personal protective equipment (PPE). A hazard index is automatically measured from spatial-temporal GPS data and displayed as a heat map. In modern BIM, the graphical depiction of dynamically determined individual values enables the automatic generation of customized safety performance reports. This proposal was not tested to upgrade work site security instantly, but it works well for verbal and visual directions to workers on site. Only if data are simulated or evaluated promptly can predictive safety planning be advantageous. It calls for regularly updated building information models that are frequently lacking in the construction industry.

The architectural, engineering, and construction (AEC) industry has used BIM extensively for concept collaboration. However, data manipulation is a threat because of its centralized paradigm. For this purpose, blockchain is a distributed strategy that offers immutable, traceable, and decentralized data storage to ensure data reliability and authenticity. Tao et al. (2022) presented a confidentiality-minded framework (CMF) for design interaction based on blockchain. The two primary breakthroughs of this study are an access control paradigm to guard against prohibited access to private BIM information in a blockchain ledger and novel techniques to ease system cooperation inside the access-controlled blockchain system. The viability and performance of the recommended CMF, which has a tolerable latency of approximately 0.004 s and a storage cost of 144KB/day, are confirmed by an illustrative design example. The findings also specify that when project participants work within the CMF, sensitive BIM data is retained favorably as private. The computational performance of the model is the primary emphasis of this research, but other qualitative variables, when applied to various real-world projects, merit additional research.

4.4. Smart building

IoT-based technology is the beating heart of intelligent buildings since it permits user data generation and data control (Kim et al., 2020). The digitization procedures aim to improve safety, productivity, and execution quality while promoting sustainable development, teamwork, and innovations for a sustainable smart town. Fig. 5 illustrates various components of a smart building, integrating IoT technologies, such as real-time analytics, cloud infrastructure, smart sensors, and connected computing. Key components include surveillance, HVAC (heating, ventilation, and air conditioning) systems, occupancy sensors, air quality sensors, and security controls. These elements contribute to the overall efficiency and safety of the building, with benefits such as energy efficiency, improved maintenance, comfort, productivity, electrical safety compliance, and enhanced data analytics.

Central digital revolutions are transforming buildings and unveiling new trends for integrating information technologies. Sophocleous et al. (2018) correlated the electrical resistivity of materials (concrete) with their moisture level using an affordable, durable, and screen-printed resistivity sensor. The sensor was examined in two individual concrete composites (vastly absorbent particles (5.1 %) and less absorbent aggregates (1.0 %)) to compare inconsistent drying rates. The sensor used an alternating square wave with a 1 mA current source at a 1 kHz frequency, which is powerful enough to preclude any polarization effects but adequate to estimate the resistivity of any electrode capacitance independently. It can distinguish various types of concrete depending on the variance in their drying rates, demonstrating a considerable correlation between the sensor's response and electrical resistivity. Because of the exceptional wear resistance of the alumina substrate, this type of sensor has a longer lifespan. It can be incorporated conveniently into a structure management platform used in smart buildings. The application of inhibitory maintenance instead of reactive maintenance may contribute to a more durable architecture by revealing important information about the critical characteristics of the building material.

Thermal imaging was recommended by Khan et al. (2019) to identify issues with a building's eggshell insulation. This technique uses thermal pictures of different building sections to pinpoint temperature fluctuations within a building. Higher temperature variation indicates inadequate insulation or surface defects in the walls. Fifty thermal photos of the inside and outside of the building, covering insulation, thermal bridging, moisture issues, and electrical outlet holes, were gathered using a FLIR ONE camera and an Android smartphone. The accuracy of the study's insulation issue identification was 75 %. However, the camera unit has a narrow field of view and a poor resolution of 16 × 4 thermal imaging pixels. As a result, a stepper motor that turns the entire system with precise motions must be mounted on top of the camera. Future research could examine the long-term effects of leakage by constantly observing the indoor environment. Sonnekalb and Lucia (2019) initiated an IoT-based smart hot water control system that operates autonomously. The system's control adjusts the heating times according to the data accumulated about users' behaviors. Neural networks and Gaussian process models were intended to compute optimum heating plans that result in substantial energy savings (20–34 % of the energy was used compared with a baseline schedule) for all users throughout a six-month test phase. Nevertheless, the authors could not forecast all users' demands due to the estimated 7 % prediction error. It can be tested with additional machine learning algorithms, such as long short-term memory (LSTM), to lower the prediction error rate further.

Jeyasheeli and Selva (2017) developed a system that utilizes temperature and light intensity to execute a lightning design that maximizes power efficiency throughout the day by eliminating fluorescent lighting and static power and reducing carbon emissions. It can adjust the power dynamically after detecting the light source and temperature through the LED and sensors. The system profits from LEDs and sensors, which recognize the light source and temperature and then dynamically adjust the power. Bright white light is produced using high-power LEDs rather than industrial tube and compact fluorescent light (CFL) bulbs. Pulse width modulation (PWM) signaling is applied to dynamically modify the power supply depending on changes in environmental light intensity. The power supply reduces over time as ecological brightness rises. Nonetheless, the system uses the same energy at night as current systems.

4.5. Disaster management

Conventional telecommunications networks (cellular or landline) may sustain complete or partial destruction following a catastrophic scenario. Humans cannot prevent calamities from happening, and the only course of action available is to create reliable prediction systems to reduce devastation and expedite disaster management operations through careful planning and the application of recent advances in information technology. Unstructured data can be produced by various sources and sent to a remote station upon request or after discovering the overall activity. However, processing these enormous volumes of diverse information during a real-time disaster event is rather complex (Akter and Wamba, 2019). Systems for managing disasters are on the verge of being outfitted with a variety of novel accommodating data sources and affordable data processing tools for strategic planning in all stages of an incident as a result of the emergence of the most recent service, data analytics, and communication technologies, such as IoT, big data analytics, cloud and fog computing (Shah et al., 2019).

Numerous research projects in flood data collection, flood detection, flood prediction, flood monitoring, and data visualization have been carried out to lessen the effects of flood disasters through early prediction. In flash flood susceptibility mapping, Costache et al. (2019) assessed the effectiveness of the K-Star (KS), k-nearest neighbors (kNN), analytical hierarchy process (AHP), and their combinations. There are 10 flash flood predictors; roughly 70 % of the areas are used as training data. Remarkably, remote sensing techniques can detect 80 % of flash flood-predicting variables. The models' performance is assessed using statistical measures such as sensitivity, accuracy, and specificity. The findings are validated by building areas under the curve (AUC) and receiver operating characteristics (ROC) values, as well as by determining the pixel density inside flash flood potential index (FFPI) classes. Overall, the kNN-AHP ensemble model outperformed with AUC= 0.944, with a prediction rate of 0.841. It is believed that this application of the KS model is the first attempt to use it to evaluate receptivity to natural disasters. Using the two ensembles to predict FFPI is considered the main innovation of the research.

Arbia et al. (2017) offered a cloud-based IoT platform for monitoring an emergency disaster aid system. To support end-to-end network connectivity, critical and rescue operations using a wearable wireless sensor network ($CROW^2$) system connects heterogeneous wireless devices (sensors and smartphones) with multiple communication protocols (Wi-Fi and Bluetooth). The ORACE-Net is on various devices, including Raspberry Pi computers running Linux and Android smartphones. Findings suggest that the $CROW^2$ system performed better than expected in terms of throughput and jitter for wireless body-to-body communications. However, the experiment does not address outdoor conditions or provide a thorough overview of the system's behavior in various environmental circumstances.

A novel algorithm for an ad hoc network connected to device-to-device communications for a post-disaster management framework was provided by Kamruzzaman et al. (2017). They also recommended integrating a disaster function in all smartphones. The smartphone automatically switches to and begins operating in disaster mode whenever a standard cellular network is broken or unusable. Users can upgrade their condition and pinpoint their location promptly to receive assistance even when the infrastructure is damaged. The system also enables battery conservation for as long as possible, delivering emergency messages or voice calls to the user. Once the need for device-to-device (D2D) communication is determined, a pre-installed program can be activated during the procedure. Relay nodes can be chosen when forming an ad hoc network, depending on the criteria mentioned and the aggregate effect of various cost considerations. For instance, any device with more processing power and remaining energy will be given preference when choosing a relay agent.

Lin et al. (2018) reported that the simulation that dictates the viability of typhoon risk evaluation performs better when Spark-based computation is used for large sets of available data. Graphic processing unit computing, multi-threading, or clustering technologies can quickly produce a significant amount of typhoon risk data and are the most cost-effective and practicable approach. The authors tried to simulate the typhoon wind field using Spark, the most recent cloud computing platform; 1038 historical wind fields were computed. Although the procedure model is not the center of this study, they anticipate extending Spark to different typhoon wind field concepts and developing a universal high-performance device that endorses all typhoon wind field models to help scientists in disaster preparedness.

4.6. Solar-assisted system

Utilizing solar energy is the most sustainable strategy to reduce stress and dependence on fossil fuels. However, to maximize power output, monitoring solar installations and adjusting their angle in real-time is necessary to achieve optimal alignment with the sun's location. IoT technology can be feasibly adopted to accomplish this (Botero-Valencia et al., 2022; Naikwade et al., 2022; Sumathi et al., 2017). To illustrate, Li et al. (2020) studied an approach to evaluating and enhancing a solar water heating (SWH) system's energy efficiency. Corresponding control plans are created for various sub-systems based on the insights gleaned through data analysis to increase efficiency and reduce operating costs. The primary monitoring sensors include solar irradiance sensors, flow meters, temperature sensors, status sensors, and electricity meters. Compared to an SWH without control during the same hot water demand time, the SWH with the recommended control mechanisms can reduce power consumption by 32.9 %. Notably, the strategies suggested in this study are appropriate for other commercially available SWHs besides the SWH reviewed.

Shapsough et al. (2020) demonstrated an IoT-based design and execution of an online monitoring and assessment system for distributed solar farms. The system employs intelligent sensors and microcontrollers to describe photovoltaic (PV) panels working outdoors, utilizing the capacitive load current voltage tracing approach. PV panels communicate data in real time using an IoT-based software architecture that provides powerful tools for large-scale data management, storage, and manipulation. Following two months of soiling, the data collected demonstrate that soiling significantly reduces the efficiency of PV modules, with an up to 40 % reduction in power production. Cleaning the solar panels to reduce costs and increase power output is feasible, as shown by an in-depth analysis of the available data. However, this is a crucial step in adopting solar energy in areas where soiling is a severe issue. The optimal angle of the solar panels varies throughout the day as the sun moves in position and angle. A simplified but precise sun position measuring system is necessary to optimize output from a solar panel and boost panel efficiency while lowering system cost. Sensor-based systems for measuring the sun's position cannot accurately determine the solar position on foggy days or during changeable weather conditions. Therefore, sun position algorithms use astronomical data or mathematical formulas to determine the sun's position at a specific place and time.

The astronomical almanac (AA) algorithm by Chowdhury et al. (2019), which can be applied in an 8-bit microcontroller, has been effectively used to construct a real-time solar positional monitoring system. The Arduino and the ATmega382P microcontroller were applied to implement the system block. According to the results, this algorithm exceeded the performance of fixed and optical tracking systems by 13.9 % and 2.1 %, respectively. Algorithm-based closed-loop dual-axis monitoring can enhance the efficacy of the system for a mini solar tracking model.

4.7. Smart grid

A smart grid is a communication network built explicitly into the power grid to collect and analyze data from the power grid (Ghasempour and Moon, 2016). A smart grid benefits a traditional power grid through the use of IoT to enhance the grid's capabilities. The application of IoT in smart grids has immense potential. IoT can be used in the advanced metering infrastructure (AMI) of smart grids, smart distribution, and transmission tower protection (Saleem et al., 2019). AMI is one of the integral parts of the smart grid. According to the US Department of Energy, advanced metering is integrated into the overall system to collect and utilize user data in real-time (Palacios-Garcia et al., 2017). The AMI allows users to access an estimation of their power consumption and make an informed decision based on this estimation. It will enable a real-time demand response system from the supply station (Chen et al., 2020). With the help of IoT, this system helps detect companies' energy consumption and pricing information and provides this to users who can use this information to save money (Gomathy et al., 2021). Along with AMI, transmission tower protection is one of the most crucial aspects of a smart grid. The traditional method for protecting transmission towers is patrolling staff, resulting in various synthetic and natural disasters such as burglary, intentional damage, cyclones, typhoons, etc. IIoT technology can be used to avoid these security issues and protect transmission towers (Saleem et al., 2019). One of the features of IIoT-aided transmission tower protection is remote monitoring. Various IIoT sensors, such as vibration sensors, anti-theft bolt sensors, video cameras, and leaning sensors, provide the supply station with data, allowing enough time for rapid action. The signals received from the sensors through sink nodes are converted to data and monitored through the communication network (Reka and Dragicevic, 2018).

IoT is frequently utilized in industrial automation, smart energy tracking, and other activities. IoT systems are placed at different phases of the smart grid to actively monitor grid statistics for distributing dependable and effective power. A system with monitoring, communication, and analytic components was proposed by Khan et al. (2020). "ThingSpeak," an IoT-based software, was applied to gather real-time electrical information from users. Depending on this information, user and electric power companies under the smart grid paradigm can regulate their consumption to lower billing costs. However, low-cost, simple-to-integrate power sensing and monitoring equipment are necessary for the large-scale deployment of the suggested system.

One of the primary concerns with the current energy metering system is that full-duplex transmission is unavailable. To solve this issue, Barman et al. (2019) designed a smart energy meter based on IoT. The recommended smart energy meter uses a Wi-Fi module to measure and manage energy use. Then, the findings are uploaded to the cloud, where the client or supplier can review the information. Arduino integrated development environment (IDE) software is used to program the Wi-Fi module to determine the pulse of the power meter. Nonetheless, the system can occasionally take a while to upload the data according to the internet speed and module baud rate.

Spanò et al. (2015) introduced a novel last-metered smart grid concept and its implementation. The authors emphasized the necessity of an embedded IoT platform for the smart grid with consumer involvement. The method comprised four unique features that give it an edge over traditional protocols: a seamless fusion of smart grid and smart home applications on a similar architecture, data collection from multiple sensors, protected and personalized data access, and unambiguous mapping of sensors and actuators to a prevalent abstraction layer that can enable various simultaneous applications. They also developed an IoT server for a customizable user interface using an IoT demonstrator based on Zigbee and trailed it with smart meters. The strength of the suggested architecture is in its inherent capacity to scale up for large-scale applications. It is facilitated by a low-cost gateway and energy meter, focusing on implementation for non-technical users. Although the proposed system is architecturally specified with a thorough explanation of the goals and objectives, insufficient information on its execution is provided.

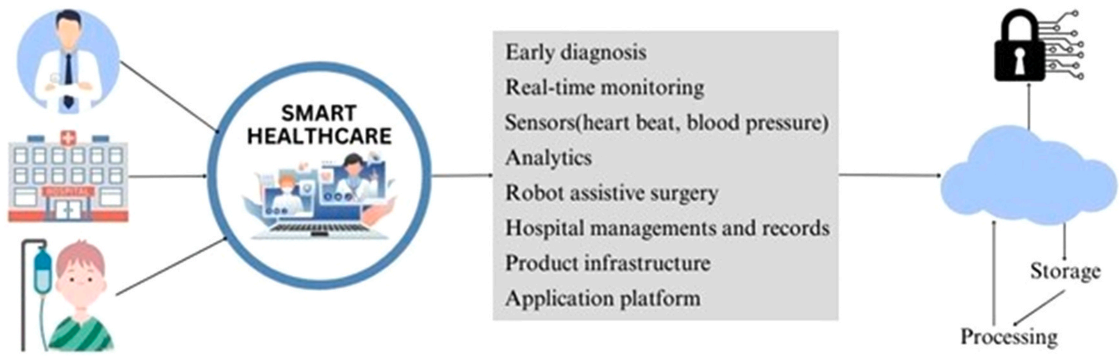

Fig. 6. Advancing smart healthcare systems utilizing IoT.

4.8. Robotics technology

IoT has recently entered the robotics and automation sphere after demonstrating versatility and effectiveness in multiple sectors and domains. Robotics involves quickly developing technology that is accepted in professional and public settings. IoT can bring about innovation and be helpful in robotics (Liu, 2019). IIoT's cognitive technologies help factories implement intelligent manufacturing and improve production processes. Context-aware cloud robotics for material handling in the cognitive IoT space was the focus of a study by Wan et al. (2018). The authors compared context-aware cloud robotics (CACR) with one-time on-demand delivery (OTODD). They used simulations to investigate the basic operations of handling materials and the design, advantages, limitations, applications, decision-making processes, and cost optimization. Using CACR for material handling can increase energy efficiency and cost savings, demonstrating the supremacy of cognitive IIoT. However, there are some security concerns with cognitive technologies, including the administration of big data, which is vulnerable to attacks in this context, and a protracted development phase, which can provide challenges in this area.

Li and Savkin (2018) introduced a safe wireless sensor network-based navigation algorithm for micro-flying robots in IIoT. A wireless sensor network of 3D range finders was applied to identify static and moving obstacles and maneuver miniature flying robots around these without colliding. It is a cost-effective and efficient approach for the IIoT's simultaneous supervision and navigation of micro-flying robots. Even though the method worked as anticipated in static and dynamic environments with numerous micro-flying robots, wireless sensors can have some downsides, including network hacking vulnerability and slow transmission, which might make them difficult to employ in an industrial setting.

Robots are considered "things" and have been connected to other objects since the dawn of IoT. The envisaged IoT and artificial intelligence solution related to Parkinson's disease presented by Sivaparthipan et al. (2020) can significantly improve gait performance. The authors outlined the function of robots in Parkinson's disease and their relevance to big data analytics. The solution was developed on the Windows 10 platform with MATLAB R2018b. The authors also introduced a laser-scanned approach with piecewise linear Gaussian dynamic time warp machine learning that can check the path for risks and secure areas. The robot's primary duties included foreseeing the patient's walker movements and providing physical therapy. The final result demonstrated a better gait detection rate than in previous research. Robotics supported by IoT is best suited for situations when real-time data from hostile settings is needed for extended periods. Robots connected to the IoT can be strategically placed to obtain high-quality real-time data, which would be impossible with detached robots. The Internet of Robotic Things is the collective name for the relationship between IoT and the robotics industry. Many other studies (Patel et al., 2018; Scaradozzi et al., 2019; Verma et al., 2018; Yukitake, 2017) have been conducted in this area.

4.9. Automotive industry

The burgeoning IoT sector is a blessing for the automotive industry since it provides a wide range of opportunities to creatively develop, build, and expand seamless services focused on the user's convenience. IoT applications in the automobile industry allow sophisticated systems like electronics, actuators, and sensors to communicate online with one another and other vehicles. Obtaining and processing data on traffic safety is a crucial component of the mobilization of transportation. However, data safety concerns due to possible intrusions in the network are still relatively new. Moussa and Alazzawi (2020) examined the organizational and implementation strategies used in dew computing by evaluating the data transmission between clouds and the end-user dew devices mounted in connected automobiles. In comparison to previous IoT methods, this was seen to bring the user closer. The researchers utilized a deep learning strategy and a tweaked stacked autoencoder, which are known to increase the accuracy of predefined threat detection. Although their approach gave 90 % accuracy, deep learning can cause difficulties, such as the need for massive training datasets and accuracy issues with unbalanced data.

Maintenance has become a significant issue as the automotive sector grows. Vijaya Shetty et al. (2017) examined an automated helper program for automotive maintenance intended to assist in identifying minor maintenance issues caused by the vehicle. This program can reduce the need for a mechanic for minor engine problems and help identify engine diagnostic trouble codes (DTCs). The study adheres to OBD-II standard protocols without utilizing any OBD-II-certified vehicles. This application makes a data mine for monitoring vehicle actions and a tool for developing relevant driving behavior profiles possible. By delivering a wide range of utilities, this application contributes to a better driving experience and a spectacular in-car experience. Population growth and the sharp rise in demand for private mobility have highlighted the need for automated parking systems that utilize computing power, fast internet connections, and interacting IoT devices. Remote locations can also make use of this. Maharjan and Elchouemi (2020) concentrated on utilizing a network where the applications could operate concurrently while exchanging data and performing computations to reduce latency and use all technologies effectively. Lowering the time spent looking for parking was made possible through the platform by combining IoT and fog computing, resulting in saved time and fuel and reduced CO_2 emissions. However, because of the encryption used, fog computing might be challenging and lead to problems with data exchange.

Balog et al. (2020) concentrated on researching the modular hybrid type of intelligent charging stations and their usage in the infrastructure of the automotive market. They suggested modular hybrid charging stations to increase demand for electric vehicles (EVs) and fulfill manufacturer and consumer expectations. The proposed device's strength is in combining sophisticated technologies to produce an entirely new product that adheres to Industry 4.0 criteria. These criteria introduce new hurdles to designers related to achieving high power density and immunity to electromagnetic radiation. The multi-layer ceramic capacitor (MLCC) is currently one of the dominant elements in the schematics used by most automotive suppliers. These capacitors are currently in low supply, hurting the electric and electronic industries. Consequently, the authors searched for other design approaches. Polyethylene naphthalate (PEN) film capacitor is an alternative to MLCC, and in many ways, PEN's qualities are similar to or superior to those of MLCC.

4.10. Healthcare

IoT is increasingly applicable in the healthcare sector, which constantly requires better techniques for service delivery, cost reduction, and quality improvement (Fig. 6). For example, the use of IoT inspires patients to adhere to self-care principles, which has led to effective cost management and better patient contentment and health management. IoT-driven solutions can be utilized for the remote monitoring of patients requiring around-the-clock care, as well as developing systems with heterogeneous entity connectivity. The healthcare sector highly depends on secure patient data with the most robust privacy protocols. With a growing population and enormous diversity of diseases, automation in the healthcare sector is becoming increasingly necessary. A model was advocated by Qamar et al. (2018) to monitor the healthcare sector to benefit patients who require but do not have ready access to extensive care services. The model described a way to seamlessly connect various systems over the internet and supply real-time, unique data and services to healthcare professionals. The authors explored popular sensor models such as body, pulse, and respiratory. However, they did not undertake a comprehensive literature review discussing the drawbacks of each technology.

Given the private nature of healthcare data, information about patient health needs to be handled delicately and sensitively. Although many methods are equipped to handle breaches during transmission, they cannot protect against collusion breaches and data leaks. The privacy threats that encompass IoT systems in healthcare were analyzed by Luo et al. (2018). The research investigated the privacy challenges in healthcare and proposed a framework named PrivacyProtector, which collects data with protection. This patient data security framework was proposed using the principles of secret data sharing and data repair sharing. They also presented a secret sharing scheme named SW-SSS. The analysis revealed that the proposed framework could ensure security and privacy using patient access control systems on servers and secret sharing. However, this model did not check the corrupted or compromised shares scenario using SW-SSS.

In the case of medical data digitization, there remain many issues and policy problems with access control structures incompatible with the security requirements of this data. Blockchain uses smart contracts and an enterprise-distributed ledger framework to observe special signs of patients. This allows medical data to be globally transmitted with better connectivity and security. However, the use of blockchain comes with unique drawbacks, such as scalability, privacy issues, and complexity. An IoT-based data management system, in the case of managing and transferring clinical sensor data using blockchain technology, was described by Wang (2020). This research proposed integrating IoT, blockchain, and cloud technologies in healthcare services. The Ethereum hybrid network certification system was used for this model, which resulted in less response time and cost than other models. Various matrices were used to analyze the proposed model, such as data security, processing time, and so on, which revealed an increment in latency reduction and overall system throughput. However, this research should have discussed the interoperability of this model in different IoT frameworks.

4.11. Coal mining

Mining is a significant industry, and the health and safety of miners are important factors in this sector. Mining is an inherently hazardous and labor-intensive task, making it essential for the industry to adopt safety strategies to protect the miners' well-being. Advances in ICT enabled the widespread adoption of wireless sensor networks (WSN) in mining as their benefits became recognized. To promote safe, sustainable, and lucrative mining operations, academics and the mining sector have gained attention to the concept of a "smart mine" (Dhar Dwivedi et al., 2021). Specifically, the autonomous features of IIoT make it ideal for time-critical applications like coal mine safety systems (Thirumal and Kumar, 2022).

The process of surface mining involves removing the rock and soil that covers the mineral deposit, known as overburden. In contrast, minerals are taken through tunnels or shafts, while underground mining leaves the underlying rock intact. The advantages of employing electricity in underground mining operations are significant since continual evacuation of harmful exhaust gases is necessary for worker health and safety. Extensive ventilation systems are not necessary when vehicles and machinery are electrified. The use of electric equipment in these settings has several benefits in addition to reducing the need for ventilation, which are far quieter, require less maintenance, have fewer parts, and emit no emissions compared to internal combustion engines (Horberry et al., 2016; Onifade et al., 2023). Furthermore, IoT-based automated technology, such as self-driving automobiles, provides essential data on the mining areas (Husain et al., 2014; Zvarivadza et al., 2024).

A system proposed by Porselvi et al. (2021) combined two concepts: one that monitored the status of miners and the other that monitored the entire section. In locations where miners work, the air is usually contaminated because of particulate matter emissions and certain gases such as SO_2, NO_2, and CO, so smoke sensors were used to detect levels of smoke in these areas. Semiconductor sensors were utilized to measure unsafe gas concentrations. Further, the proposed system can also access the workers' medical data and use this data for future medical records. Information was passed through a LoRaWAN module that allowed low-powered entities to communicate through IoT. This system was found to have improved optimization, capacity, durability, and cost-effectiveness.

Sensors installed in surface and underground mines can detect damaged equipment, anticipate possible issue areas, and forecast system instability and dysfunction in mine access areas like shafts. This knowledge contributes to sustaining and preventing any mishaps that could occur from ignorance or the extraction of resources (McNinch et al., 2019). Using IoT-enabled sensors and a convolutional neural network (CNN)-LSTM model, Dey et al. (2021) proposed a prediction model for improving the safety and utility of underground mines. The model extracted spatial and temporal information from mining data, predicted many mine hazards, and improved flexibility, scalability, and monitoring areas in remote locations. It also predicted the health condition of the workers. The CNN-LSTM showed better performance than the existing models. However, CNN requires large training datasets, which can be problematic. Savitha et al. (2021) suggested a system that builds an effective safety technology using IoT technology for the coal mining environment. The system uses different sensors placed in different locations in the mine that collect real-time data. This data can be used to monitor any changes in the mining environment and send alarms to the workers as required. However, this model was implemented only in a laboratory setup with minimal hardware equipment. In a real situation, the environment might generate vast amounts of data, which could necessitate the application of different and more efficient tools.

While automation may lead to job losses in traditional roles, it also creates new opportunities in tech-related fields. By investing in upskilling and reskilling programs, workers can transition into advanced

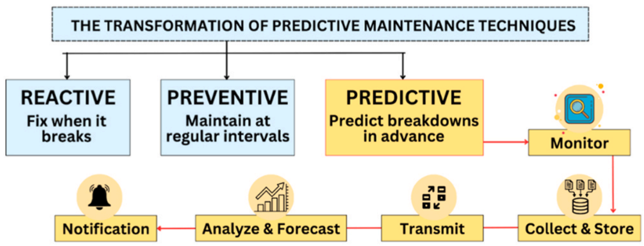

Fig. 7. The transformation of maintenance techniques in the industry.

roles like automation specialists or data scientists, ensuring they stay relevant in a changing job market. This shift helps workers adapt and enhances local economies, particularly in regions dependent on industries like mining, by encouraging innovation and reducing reliance on a single sector. Ultimately, employees and businesses benefit from a more skilled and versatile workforce.

4.12. Emergency response systems

Underground miners' health has been a significant challenge to overcome in the case of emergency response systems. In addition to cost-profit optimization, the safety of miners must be a priority. Using the IoT standard architecture, Maguluri et al. (2018) recommended a system for responding in the midst of an emergency involving risks such as fire and smoke. To utilize this proposed mechanism, a low-cost, usable Wi-Fi module ESP-32, a detection sensor for fire and smoke (MQ-5), a detection sensor for flammable gas, and a GPS module are required. By sending locations through the cloud, the sensors look for hazardous elements and alert authorities such as local emergency response units, fire departments, or law enforcement agencies. The network uses a lightweight data-based protocol named MQTT for fast and reliable communication. The authors demonstrated that an IoT-standardized structure can be used to develop an emergency response system for fire hazards. However, even though MQTT uses transport layer security (TLS)/secure sockets layer (SSL), it is primarily unencrypted.

IoT is also utilized for urban emergencies, which are hard to avoid. A response system for addressing traffic emergencies can significantly reduce the loss of life and property damage. Traditional methods have failed in many such complicated contexts. Liu and Wang (2019) proposed an IoT and data mining system to improve urban emergency response and data management levels. The framework involved sub-systems, including vehicle data, evacuation data, rescue resource data, and so on. They also developed programs for managing commands, emergency support, and other tasks. In this proposed model, IoT and data mining could control incoming information accurately and quickly, relocate people and vehicles, and command rescue activities. However, the system is complicated with data acquisition, errors, and insufficient optimization of algorithms, all of which need to be solved.

4.13. Predictive maintenance

The productivity of manufacturing processes worldwide has increased significantly in recent years due to the integration of robotic and autonomous technology (Stock and Seliger, 2016). These platforms count on the smooth function of the machinery, and a failure in any subsystem or component may disrupt the production line as a whole. Such disruptions can arise from various factors, including equipment malfunctions, operator mistakes, or environmental conditions. However, predicting these issues in advance can lead to solutions proactively, preventing production stoppages and leading to significant cost savings (Yu et al., 2020). Fig. 7 depicts the evolution of industrial maintenance techniques, starting with reactive maintenance, where repairs happen post-failure. It advances to preventive maintenance (PdM), characterized by scheduled interventions to avoid breakdowns, and culminates in predictive maintenance, which leverages data collection and analysis to anticipate failures.

PdM is a modern strategy aimed at enhancing the performance and efficiency of manufacturing processes by extending equipment lifespan and supporting sustainable operational management. The fundamental idea is to foresee the upcoming failure to allow maintenance in advance. Reducing maintenance costs while maintaining continuous and effective operations has become a priority for the industry (Ayvaz and Alpay, 2021; Stock and Seliger, 2016). Moreover, PdM contributes to sustainability by optimizing the utilization of production equipment and maximizing its useful life (Song and Moon, 2017).

Data flexibility and sensor data processing are critical challenges in PdM, as unlabeled and sparse data can hinder algorithm performance. Identifying anomalies in high-dimensional IoT data is difficult, especially in noisy big data environments. Despite these challenges, AI-driven applications using IoT data can aid PdM. Ayvaz and Alpay (2021) developed a machine learning-based PdM system to predict potential production line failures by comparing multiple algorithms using real-world data. The suggested PdM system for manufacturing utilizes processed real-time IoT data through an infrastructure integrated with ML models. Sensor data from production lines was normalized and preprocessed to address imbalanced data. Several ML algorithms were evaluated with dimensionality reduction via principal component analysis (PCA), and hyperparameters were tuned using random search with cross-validation. Random Forest outperformed other models ($R^2 = 0.982$), while gradient-boosted decision tree (XGBoost) and AdaBoost showed suboptimal performance ($R^2 < 0.35$). While the equipment used is industry-standard, applying the model in diverse circumstances is needed to ensure broader applicability. Moreover, the model primarily addresses common failure scenarios, and future research should aim to include rare failure categories.

PdM schedules tend to be excessively conservative, often resulting in unnecessary modifications to optimized components. It raises labor costs, resource waste, and production interruptions during scheduled maintenance periods. By detecting early equipment failures through continuous condition monitoring and data analysis, PdM enables timely, targeted interventions, reducing downtime and extending equipment lifespan. Abouelyazid (2023) introduced a real-time PdM framework for industrial IoT systems, leveraging advanced AI techniques. The approach involves continuous data collection from IoT sensors, such as vibration, temperature, and acoustic emissions, with machine learning (ML) and deep learning algorithms. AI models are trained to detect anomalies and estimate machinery's remaining useful life. The system is cloud-based for real-time action and combines data from different sensors to give more accurate predictions. CNNs are great at figuring out complicated patterns, while LSTMs are the time-trend experts, helping predict when things might go south. Hence, they avoid unexpected breakdowns, save on maintenance costs, improve efficiency, and extend machine life.

IoT-driven PdM is an evolving field with promising potential to revolutionize industrial processes. Future studies should concentrate on developing affordable IoT solutions for small and medium-sized enterprises and investigating how to integrate IoT with cutting-edge technologies like blockchain for improved security. IoT will require constant research on the long-term implications of its deployment. Collaboration between policymakers, academic researchers, government, and industry stakeholders is crucial to reach its full potential.

A summary of recent studies conducted on IIoT is given in Table 3, including outcomes, applications, and weaknesses/strengths.

In summary, the sectors mentioned above have been revolutionized by the Industrial IoT. Real-time monitoring and control are made possible by IIoT due to connected sensors, automation, and data analytics, which ultimately optimize resource utilization, reduce environmental impact, and increase safety. It helps with disaster mitigation, smart building energy management, energy efficiency on construction sites, and precision agriculture. The Industrial IoT also helps shape a

Table 3
Summary of recent studies conducted on IIoT.

Applications	Architecture/ module/ sensors	Objective	Outcome/accuracy	Strengths/weaknesses	Ref.
Environmental monitoring	Cloud-based software, environmental sensors, and a smart box.	Innovate an IoT-based smart system for fire and other dangerous circumstances.	The system transmits information to the cloud to be processed in every way.	A complete infrastructure leveraging open-source protocols (MQTT, REST) to control data transactions can be made in the future.	(Cavalera et al., 2019)
	ThingSpeakIoT, GPS, Arduino, Raspberry Pi.	Invent an IoT-based environmental monitoring system.	The system sends 15-second updates to the IoT server for sensor documentation.	Cost-effective (<80 USD), and the technique can be integrated into contemporary drone technology.	(Jhansi Rani et al., 2020)
	Multi-sensory platform, microprocessor, memory module, solid-state micro-battery.	Make a non-invasive wearable platform to monitor the oceanic environment.	Persists up to 2 km depth in highly saline Red Sea water.	Does not hinder the tagged animals' normal behavior.	(Shaikh and Hussain, 2019)
Agriculture	WSN, GUI, router, server, database.	Provide a WSN application for the food industry that allows remote environmental monitoring in the agro-industry.	Measurement points at various places are necessary for quality control with warmth and other condition monitoring.	Future studies could exploit the potential of data analysis and an IoT-based network.	(Tervonen, 2018)
	The reservoir water level sensor, electro-pump controller, and 4-state switch are used.	Experiment with a multi-intelligent system for water management using IoT.	Maximum 60 % water can be saved.	Using MICS with its study design, significant amounts of money and water can be saved.	(Hadipour et al., 2020)
Construction	RFID, big data, and cloud computing.	Build a BIM platform for on-site services in pre-made construction.	Offers prefabricated stakeholders a tool to monitor regular decision-making, coordination, and inspection.	Does not consider data on productivity and the work environment.	(Li et al., 2018)
	Blockchain.	Devise a CMF for collaborative BIM design using blockchain.	Has a tolerable latency of approximately 0.004 s and a storage cost of 144KB/day.	The computational performance of the model is the primary emphasis of this research, but other qualitative variables, when applied to various real-world projects, merit additional research.	(Tao et al., 2022)
Smart building	Sensor.	Correlate the electrical resistivity of concrete with its moisture level.	Can distinguish various concretes depending on their varying drying rates.	Applying inhibitory rather than reactive maintenance may contribute to a more durable architecture.	(Sophocleous et al., 2018)
	Neural networks and Gaussian.	Develop a smart hot water control for minimal energy consumption.	Substantial energy savings for all users of between 20 % and 34 % of the power consumed compared with a baseline schedule.	Approximately 7 % were unable to forecast all user demands. The system could be tested with additional machine learning algorithms (i.e., LSTMs) to lower the prediction error rate.	(Sonnekalb and Lucia, 2019)
	LEDs, PWM.	Assess flash flood susceptibility using machine learning, multi-criteria, and decision-making.	The power supply reduces over time as environmental brightness rises.	At night, the system consumes the same energy as the current system.	(Jeyasheeli and Selva, 2017)
Disaster management	Graphics processing unit, clustering, Spark	Introduce a high-performance computational strategy to stimulate typhoon wind fields.	Evaluating trends and values for the 10-minute average. Wind time series, the observed and simulated wind speeds are consistent.	Developing a universal high-performance device compatible with all existing models of typhoon wind fields.	(Lin et al., 2018)
	$CROW^2$, Raspberry Pi, Linux.	Enhance end-to-end IoT-enabled disaster relief systems.	The $CROW^2$ system performed better than expected in terms of throughput.	The experiment does not address any outdoor conditions and, as such, does not provide a thorough overview of the system's behavior in various environmental circumstances.	(Arbia et al., 2017)
Solar-assisted system	Sensors and electricity meters.	Enhance the energy efficiency of solar water heating systems.	The SWH, with the proposed control mechanisms, can reduce power consumption by 32.9 %.	Appropriate for other commercially available SWHs.	(Li et al., 2020)
	Sensors and microcontrollers.	Analyse city-wide solar power facilities using a remote IV tracing system.	Significantly reduces the efficiency of PV modules, with 40 % power loss.	The system reduces costs while increasing power output by conducting an in-depth data analysis. However, it is a crucial step in adopting solar energy in areas with severe challenges.	(Shapsough et al., 2020)
Smart grid	ThingSpeak.	Monitor, measure, and analyze electrical characteristics.	User and electric power companies can regulate their consumption to lower billing costs.	Low-cost, simple-to-integrate power sensing and monitoring equipment are necessary for the large-scale deployment of the suggested system.	(Khan et al., 2020)
	Arduino.	Make the full-duplex transmission available in the current energy metering system.	Consumer energy analysis becomes considerably more feasible and manageable.	The system can occasionally take a while to upload the data.	(Barman et al. 2019)
Robotics technology	CACR, OTODD.	Provide context-aware cloud robotics for material handling in the cognitive IoT.	Can increase energy efficiency and cost savings, demonstrating the supremacy of cognitive IIoT.	Security concerns include the administration of enormous data and the protracted development phase.	(Wan et al., 2018)

(continued on next page)

Table 3 (*continued*)

Applications	Architecture/ module/ sensors	Objective	Outcome/accuracy	Strengths/weaknesses	Ref.
	Network-based navigation algorithm.	Provide safe wireless sensors for micro-flying robots in IIoT.	A cost-effective and efficient approach for the IIoT's simultaneous micro flying robots' supervision and navigation.	Network hacking and slow transmission might make employment in an industrial setting difficult.	(Li and Savkin, 2018)
Automotive industry	Deep learning strategy. tweaked stacked autoencoder.	Evaluate data transmission between clouds and end-user devices mounted in connected automobiles.	Increase the accuracy of predefined threat detection to 90 %.	Deep learning may provide difficulties, such as the need for massive training datasets and accuracy issues with unbalanced data.	(Moussa and Alazzawi, 2020)
	MLCC.	Asses the modular hybrid type of intelligent charging stations and their usage in the automotive market.	Ability to combine sophisticated technologies to produce an entirely new product.	Focuses only on the development of the automotive industry within the European Union.	(Balog et al., 2020)
Healthcare	Body sensors, pulse sensors, and respiratory sensors.	Monitor the healthcare sector to benefit patients who require but do not have ready access to extensive care services.	Eliminates distance barriers by giving access to remote rural communities.	Did not compile a comprehensive literature review discussing the drawbacks of each technology.	(Qamar et al., 2018)
	Ethereum hybrid network certification system.	Propose a system integrating IoT, blockchain, and cloud technologies in health care services.	Increment in reduction of latency and overall throughput of the system.	Does not discuss the interoperability of this model in different IoT frameworks.	(Wang, 2020)
Coal mining	LoRaWAN.	Monitor the status of miners and the entire sector.	Can measure unsafe gas concentrations and acquire medical data with better capacity and cost-effectiveness.	The protection of the received data that will be uploaded to a web page is not addressed.	(Porselvi et al., 2021)
	CNN-LSTM.	Improve the safety and utility of underground mines.	Showed better performance than other existing models.	CNN requires large training datasets, which can be problematic.	(Dey et al., 2021)
	Arduino	Build an effective safety technology using IoT for coal mining.	Can be used to monitor any changes in the mining environment and send alarms to the workers.	Was implemented only in a laboratory setup where minimum hardware equipment was used.	(Savitha et al., 2021)
Emergency response system	Wi-Fi module ESP−32, MQ−5, and GPS module.	Respond to emergencies involving risks such as fire and smoke.	Has better security and data distribution compared to other models.	Primary unencrypted security layer.	(Maguluri et al., 2018)
	Data mining.	Improve levels of urban emergency response and data management.	Can control incoming information with accuracy and speed.	The algorithm is complicated and insufficiently optimized.	(Liu and Wang, 2019)
Predictive Maintenance	ML algorithms, PCA	Predict disruptions in the production line before they occur.	Effective in forecasting production stops using real-world data.	It should have been tested in more diverse failure scenarios for generalization.	(Ayvaz and Alpay, 2021)
	IoT Sensors, AI, ML, deep learning	Exploring the role of real-time anomaly detection in ensuring the efficacy of AI-powered PdM systems.	Can identify important KPIs, such as speed, as key drivers for detecting machine errors.	CNNs are great at figuring out complicated patterns, while LSTMs are the time-trend experts. Therefore, they are saving on cost and extending machine efficiency/life.	(Abouelyazid, 2023)

more efficient, interconnected, and resilient world by improving industrial automation and robotics, healthcare delivery, mining safety, and emergency response times.

5. Comparative analysis of IIoT implementation across various fields

This section compares the performance of IIoT in terms of the advantages and limitations across many different fields, from agriculture to disaster management to environmental monitoring to healthcare. It is expected that by illuminating the specific benefits and difficulties experienced by each industry, readers will gain a deeper understanding of the far-reaching effects of IIoT. The research highlights the revolutionary potential of IIoT and the necessity of addressing sector-specific limitations to realize its potential fully.

A wireless sensor network-based method for the irrigation of crops was suggested by Muangprathub et al. (2019). A control framework was developed in the study that used node monitoring devices in an agricultural field and enabled the management of data through smartphones and a web-based application. The results demonstrated the significance of the implementation in agriculture by keeping the soil moist enough for vegetable growth while decreasing expenses and increasing output. Wireless sensor networks (WSNs) may find it challenging to adapt to rapidly shifting environmental conditions due to their low adaptability. For example, unpredictable weather or soil changes can reduce the efficacy of pre-programmed watering schedules. For agricultural surveillance in the context of precision agriculture, Popescu et al. (2020) proposed a hierarchical structure based on coordination between unmanned aerial vehicles (UAVs) and integrated WSNs. The cooperative UAV-WSN-based IoT approach improved efficient and ecological production. However, a number of challenges prevent such a collaborative system from being implemented, including limited sensor coverage, limited communication coverage by the integrated UAV-based WSN system, high energy consumption, and inefficient processing.

The IIoT has proven to be an important infrastructure component in disaster management and environmental monitoring. For instance, Bushnaq et al. (2021) designed a UAV-IoT architecture to detect wildfires. The efficiency and dependability of UAV-IoT networks in detecting wildfires were assessed, and a strategy was developed for optimizing the IoT-based UAV system to raise the potential of correct fire identification. Increasing the number of UAVs improved fire detection capability, while increasing the number of IoT devices consistently increased the rate of detection. However, there may be restrictions, such as a high chance of false alarms or failure to detect something. However, due to IoT monitoring technologies, digital sensors can now keep tabs on the composition and architecture of various environmental elements in real time,

Table 4
Advantages and limitations of implementing IIoT in surveyed fields.

Application/field	Advantages	Limitations	Reference
Agriculture	– Maintain the soil's moisture content adequately. – Lower the costs and raise agricultural output.	Low adaptability	(Muangprathub et al., 2019)
	– Cooperative UAV-WSN-based IoT approach improves efficient and ecological production.	– High energy consumption – Mediocre processing efficiency	(Popescu et al., 2020)
Disaster management	– Cost-efficient – Substitute satellite photography for detecting wildfires.	– Missing detection and false alarm probabilities	(Bushnaq et al., 2021)
	– Highly applicable to earthquake emergency management through infrared illumination variation in temperature.	– Highly complex nature of the earthquake and numerous challenges with earthquake rescue could make it difficult to utilize the functions effectively	(Cheng et al., 2020)
Environmental monitoring	– Improve the quality and level of environmental monitoring. – Can successfully deal with the inefficiency and low reasoning associated with conventional environmental monitoring.	– Challenging to ensure uninterrupted interaction and compatibility	(Song et al., 2016)
	– Sufficient transmission range in agricultural areas – Each node's loss rate of packets could be managed.	– - Lack of energy efficiency – Security and Privacy	(Dong et al., 2022)
Smart building	Allow each device to be identified by its address	– High upfront expenses – Cybersecurity risks – Need for an uninterrupted internet connection and accessibility	(Kumar et al., 2021)
Smart grid	– Continuous Electrical Supply – Energy Management – IoT communication – Identification of Microgrid Faults	– Can provide an overwhelming volume of data from several sources – Might be challenging to analyze and draw valuable conclusions	(Friansa et al., 2017)
Healthcare	– Transmission of real-time sensor data from the environment to the cloud via a fog layer served as an administrator.	– Illegal access – Data manipulation – Cyberattacks	(Malik et al., 2020)
	– Reducing latency – Lowering data delivery costs – Speeding up medical services in both temporal and spatial terms	– Lack of security – Decreasing data confidentiality	(Mani et al., 2020)
Automotive industry	– Improve security – Superior computing efficiency – Less expensive communication costs	– Compatibility problems and challenges	(Khalid et al., 2021)
	– Early identification of irregularities – Production line precision – Machinery effectiveness	– Integration complexity – Security risks	(Gopalakrishnan and Kumaran, 2022)
Robotics technology	RSSI method is simple yet effective for IoT-based robotics	RSSI positioning can estimate relatively low accuracy and security	(Bae, 2019)
	– Capability of selecting and positioning things – Using ultrasonic sensors to constrain the robotic arm's operational range	– Security issue – Maintenance Complexity	(Ahmed et al., 2021)
Solar-assisted system	– Effective energy management – Enhance solar panel performance – Lower operating expenses – Higher system dependability	– Scaling the system may cause problems with data handling, communication, and performance.	(Parveen et al., 2018)
	– Reliable and cost-effective – Scalable – Detailed, thorough, secure monitoring	– Integration complexity – Security risks	(Ali, 2023)
Construction industries	Revenue growth, cost reduction, and efficiency improvements	Enormous data generation	(Vijayakumar, 2021)
	Wide-area control, industrial effectiveness, high accuracy, continuous functionality, dependable operation, and affordable	– Preliminary investment and expenses – Sophisticated implementation – Network dependability and connectivity	(Plant, 2020)
Emergency responses	Information about traffic congestion, route update notifications, and compilation of emergency messages	– Concerns with Reliability – Dependence on a Network – Data Anomaly	(Shah et al., 2020)
	– Highly effective evacuation process – Minimal casualties – Cautioning about the casualty – Evacuation guidance and ease of navigation	– Flaws in security – Integration Difficulty – Sharing of Data and Privacy	(Zualkernan et al., 2019)
Coal mining	– Enhances the network's lifetime – Utilizes over 80 % of the system's average energy	– Issues with compatibility – reliability issues – substantial initial expenses	(Thirumal and Kumar, 2022)

lightening the load on ecological surveillance personnel while improving monitoring results. Wireless data transmission was used to design a system for monitoring pH and temperature in water (Song et al., 2016). Transmission stability in the envisioned sensor system was found to be relatively stable through experimental analysis. The inefficiencies and lack of reasoning inherent in traditional environmental monitoring methods were thought to be eliminated with the introduction of IoT technology, leading to a significant improvement in the quality and level of environmental monitoring. However, environmental monitoring may use a wide range of sensors, devices, and information sources from various manufacturers. Ensuring continuous interaction and compatibility between these components may be difficult and require standardization efforts.

A renewable and safely constructed smart building architecture of IIoT was demonstrated by Kumar et al. (2021). One of the most crucial web transfer protocols, constrained application protocol (CoAP), does

Table 5
Identified research challenges and their potential solutions for Industrial IoT.

	Challenges	Potential solutions
Reliability and resilience	IIoT systems must maintain operation despite interruptions or failures, as industrial processes require high reliability and resilience.	Architectures for the IIoT that can recover from errors independently should be a primary study area. Predictive maintenance, real-time monitoring, and redundancy are all ways to improve the stability of IIoT networks.
Ethical and legal considerations	Data ownership, consent, and accountable AI use are all complicated by the IIoT.	Ethical guidelines and legal frameworks designed for IIoT should be developed as part of ongoing research to address these issues. Ethical and legal risks can be reduced by using responsible AI algorithms and open data practices.
Security and privacy	Security vulnerabilities in IIoT infrastructure could compromise sensitive information or slow down production.	Robust security mechanisms, such as encryption, authentication, and intrusion detection systems, should be the focus of academic research. In addition, confidential data can be protected by using privacy-preserving methods.
Cost-benefit analysis	IIoT implementation is most difficult when quantifying and assessing IIoT solution benefits and costs.	The long-term value and efficiency gains associated with IIoT adoption can be demonstrated through research into cost-benefit analysis models and business strategies.
Data management and analytics	Large amounts of data are produced by IIoT, which makes it challenging to manage and analyze data efficiently.	Data compression techniques, advanced data storage solutions, and scalable analytics platforms can aid the management and obtaining of valuable insights from IIoT data.
Human-machine interaction	Improving human-machine interaction in work environments is challenging for successful IIoT implementation.	By studying collaborative robotics, augmented reality applications, and intuitive user interfaces, improved human-machine interaction is possible.
Environmental impact	Effects of IIoT on the environment can increase electronic waste and power consumption.	The environmental impact of IIoT systems can be minimized through investigations into green technologies, recyclable parts, and efficient designs.
Energy efficiency	Industrial environments are highly challenging to optimize and integrate because of the vast interconnected systems.	IIoT devices can last longer with energy-efficient hardware and low-power communication protocols. Research should also focus on energy harvesting to power IIoT sensors with ambient energy.
Interoperability	Many devices and systems in IIoT ecosystems are not always compatible or can not easily communicate with one another.	Interoperability can be improved by standardization and open protocols. Research should develop middleware and gateways to connect devices and platforms.
Real-time data processing	Issues arise when trying to process data in real time using IIoT because of the vast amount of data being produced by IoT devices.	Edge and fog computing can reduce latency by processing data closer to the source. Research should also examine efficient algorithms and data processing methods for real-time decision-making.

not transmit data over encrypted channels but does allow each device to be uniquely identified by its address. Automatic key management, security, authorization, and data precision were all features of the Datagram Transport Layer Security (DTLS). The authors looked at enhancing the security of the DTLS framework by combining it with the Secure Hash Algorithm (SHA-256) via CA-provided optimizations. While it had some benefits, it also had some drawbacks, like high initial costs, cybersecurity risks, the need for a constant internet connection, and limited accessibility. The healthcare monitoring sector also benefited greatly from the use of IIoT. Malik et al. (2020) proposed an IIoT strategy to efficiently process information related to structural health monitoring by building an architecture that linked data from noninvasive assessment sensors with real-time processing techniques. A system architecture was presented for transferring environmental sensor data in real-time to the cloud via a fog layer. While this information is crucial to society, it must be protected from unauthorized access, manipulation, and cyberattacks that could compromise critical infrastructure.

Several studies have highlighted the benefits and drawbacks of implementing IIoT in various industries, such as automotive, robotics, and solar-assisted systems. Khalid et al. (2021) proposed a unified multi-factor cross-domain authentication approach for IoT implementations in the automotive industry, especially car-sharing systems, by extending the Kerberos workflow with the Advanced Encryption Standard (AES) - elliptic curve cryptography (ECC) algorithm. Evaluations of the proposed approach's capabilities and performance revealed that it provided increased security, greater computing efficiency, and reasonable communication costs. These outcomes were possible because the AES-ECC algorithm uses a fast, lightweight cryptographic operation that is well suited to the context of the IoT. However, there are also potential drawbacks, such as incompatibility issues and difficulties in providing uniform user experiences across different makes and models of vehicles. Bae (2019) proposed demonstrating the efficacy of the trilateral methodology by incorporating it with relative signal strength indication (RSSI), applicable to robotics and the IoT. An RSSI algorithm customization estimation using a real-world device that employs Bluetooth technology for transmission and reception, and a beacon-based gateway, was also a major focus of the research.

In the context of solar-assisted systems, Parveen et al. (2018) proposed an IoT-based monitoring framework that would use solar power to continuously track and analyze data from multiple metrics related to solar panels in real-time. Effective energy management, improved solar panel performance, reduced operating costs, and increased system dependability were all benefits of the system. Further, the device could help people make more informed decisions about their energy consumption, lowering their carbon footprint. However, expanding the solar power system or adding sensors to the monitoring network may make managing and developing the IoT infrastructure more challenging. Data management, network, and performance issues could arise as the system scales. The advantages and limitations of implementing IIoT in the surveyed fields are summarized in Table 4.

6. Research challenges and potential solutions for Industrial IoT

The Industrial IIoT has the potential to significantly transform various industries by improving productivity, efficiency, and overall operational processes. Nevertheless, numerous research challenges must be addressed to achieve maximum potential for the Industrial IoT. The research challenges and their possible solutions are tabulated in Table 5.

7. Conclusion

Industrial IoT implementations across numerous sectors were thoroughly investigated in this review. Combining cutting-edge technology with contemporary manufacturing practices has ushered in a new era of longevity and financial success. All analyzed sectors revealed that IIoT has had a major effect on displacing long-established norms. The advantages of IIoT applications, which allow for advanced levels of real-time data collection, analysis, and remote management, are evident. For instance, in environmental monitoring, IIoT enables real-time tracking of ecological changes, facilitating quicker, more informed responses that are critical for sectors like agriculture, where precision and speed are essential. In precision farming, IIoT allows for more efficient resource management and increased crop yields by enabling detailed, data-driven insights into soil conditions and climate. The construction industry has seen enhanced project management, safety, and operational efficiency through IIoT, contributing to reduced risks and cost savings. Smart buildings benefit from more sustainable energy usage and improved occupant experiences, while solar-assisted systems have reduced their power consumption by 40 %, and smart grids have reported reductions in billing expenses, demonstrating IIoT's significant role in boosting efficiency and cost savings in the energy sector. In the automotive industry, IIoT has revolutionized threat detection, achieving a 90 % accuracy rate, enhancing safety and operational performance. Emergency response systems and disaster management have dramatically improved response times and coordination due to IIoT's ability to provide real-time data and remote management capabilities.

The IIoT holds immense potential for improving productivity, sustainability, and flexibility across a range of industries. However, its rapid technological development presents both advantages and challenges. Data security concerns, high initial costs, regulatory barriers, and compatibility issues could hinder widespread adoption, especially among smaller enterprises. To fully realize the potential of IIoT, cooperation between technology providers, businesses, and governments is essential, emphasizing strong cybersecurity, data sharing, and industry standardization. Looking ahead, future research should focus on several critical areas. First, advanced cybersecurity measures need to be continually developed to protect growing networks of connected devices. Secondly, research into cost-effective solutions will be vital in ensuring that IIoT systems are accessible to small and medium-sized enterprises (SMEs), helping them to overcome the financial burden of implementation. Third, exploring scalable standardization frameworks that can be universally adopted will facilitate smoother interoperability across industries and regions. Additionally, studies investigating the social and environmental impacts of IIoT systems could help maximize their positive outcomes while minimizing potential downsides, such as increased energy consumption or data privacy issues. Despite the challenges, the use cases already demonstrated by IoT solutions show how industries and society are becoming more interconnected and intelligent. Further research and development will drive the IIoT toward more efficient operations, reduced environmental impact, and improved quality of life for workers. Ultimately, continuous innovation and collaboration are key to overcoming current barriers and fully harnessing the transformative power of IIoT.

CRediT authorship contribution statement

Sabiha Jannat Rafa: Writing – original draft, Investigation, Formal analysis. **Shaila Afrin:** Writing – original draft, Investigation, Formal analysis, Conceptualization. **Tasfia Farah:** Writing – original draft, Formal analysis. **Maliha Kabir:** Writing – original draft, Investigation. **Aiman Lameesa:** Writing – original draft, Investigation. **Md. Sakib Bin Alam:** Writing – original draft, Methodology. **Amir H. Gandomi:** Writing – review & editing, Supervision. **Shams Forruque Ahmed:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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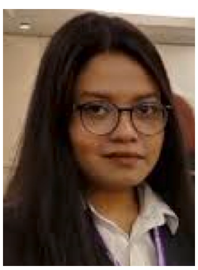

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