State-of-the-Art Comparison of Sensors in Industry 4.0, Industry 5.0, and Low-Cost Monitoring Technologies

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ARTICLE INFO	ABSTRACT
	Industry 4.0 has transformed modern manufacturing by incorporating internet-connected devices, artificial intelligence, cyber-physical platforms, and advanced data analysis. These innovations have raised automation levels, improved operational performance, and enabled predictive maintenance. Industry 5.0 builds on these foundations by emphasizing collaboration between humans and intelligent machines, promoting environmentally responsible practices, and supporting personalized production models. In parallel, affordable sensor technologies are gaining traction due to their low cost and practical ability to support essential monitoring across diverse applications. This study offers a comparative evaluation of sensor technologies in Industry 4.0, Industry 5.0, and budget-conscious systems, outlining their advantages, limitations, and areas of application. The findings suggest that sensor integration remains central to industrial progress, particularly when linked with IoT, artificial intelligence, and edge-computing solutions that enhance adaptability and real-time decision-making.

1. Introduction

The concept of Industry 4.0 has redefined manufacturing by integrating advanced digital technologies into production systems. Central to this transformation are cyber-physical systems, the Internet of Things, cloud computing, and big data analytics, which together form highly automated and connected environments [1,2]. These technologies enable more flexible production processes, improve efficiency, and support predictive maintenance [3]. As a result, Industry 4.0 has been recognized as a milestone in the modernization of industrial practices worldwide [4].

In recent years, the discussion has expanded toward Industry 5.0, which introduces a renewed focus on human–machine collaboration, environmental sustainability, and resilience in production [5]. Unlike Industry 4.0, which primarily emphasizes automation and connectivity, Industry 5.0 highlights the integration of human creativity and decision-making with the precision of intelligent

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systems [6]. This shift represents an effort to balance technological advancement with social and environmental priorities.

Alongside these industrial revolutions, the development and deployment of sensors play a crucial role in enabling smart factories and advanced monitoring systems. Sensors act as the foundation for data collection, supporting real-time analysis and decision-making processes across manufacturing, logistics, and quality control [7,8]. Both high-performance industrial sensors and cost-effective alternatives have been employed to expand access to digital transformation [9,10]. Low-cost sensors, despite their limitations in precision, have gained popularity for IoT applications, environmental monitoring, and process optimization in small and medium enterprises [11,12].

The comparison of Industry 4.0, Industry 5.0, and low-cost sensor systems is essential for understanding how technological innovation is shaping modern industries [13-15]. By examining their respective strengths, limitations, and application domains, this study aims to provide a comprehensive perspective on the evolution of sensor technologies and their contribution to industrial development [16-18]. Furthermore, the integration of emerging fields such as artificial intelligence (AI), edge computing, and advanced communication networks is expected to expand the role of sensors in future industrial solutions [19,20]. This sets the stage for identifying opportunities and challenges that will influence the next phase of industrial transformation [21,22].

2. Industry 4.0, Industry 5.0, and Low-Cost Sensors

The rapid progress of digital technologies has encouraged researchers and practitioners to investigate how industries are being reshaped by sensor-based systems. Studies on Industry 4.0 underline the role of smart devices, real-time communication, and cyber-physical platforms in achieving efficient and adaptive production environments [2]. These technologies have created opportunities for flexible manufacturing, predictive capabilities, and greater system connectivity [4]. At the same time, scholars note that challenges such as interoperability, cybersecurity, and data governance continue to influence the pace of adoption [10].

Research on Industry 5.0 emphasizes a more balanced perspective, where the integration of humans, machines, and digital platforms is guided not only by efficiency but also by sustainability and resilience [6]. This vision highlights the importance of user-centered solutions, greener production methods, and adaptive systems that can withstand disruptions. The academic discussion suggests that Industry 5.0 should be viewed as a complement to Industry 4.0 rather than a replacement, expanding the digital transformation toward human-driven and environmentally conscious practices.

Another growing body of work addresses the significance of low-cost sensors in extending digital innovation to small and medium enterprises. Although less precise than advanced industrial equipment, such devices are increasingly deployed in areas like air quality monitoring, energy efficiency management, and smart logistics. These applications demonstrate how cost-effective solutions can bridge gaps between high-end technologies and resource-limited organizations.

Overall, the literature reveals three parallel directions: Industry 4.0, which focuses on automation and digital connectivity; Industry 5.0, which integrates sustainability and human collaboration; and low-cost sensor applications, which democratize access to digital tools. Examining the connections between these approaches allows for a clearer understanding of their collective impact on industrial transformation.

2.1 Industry 4.0 and the Role of Sensors

Industry 4.0 relies on sensors as the foundation of intelligent production systems. Sensors are

responsible for capturing operational data, enabling machines and devices to communicate, and providing the inputs required for advanced analytics. They support predictive maintenance by identifying anomalies before failures occur, facilitate quality control by ensuring consistency, and improve safety by monitoring environmental and machine conditions.

Different types of sensors are used depending on the application. For example, temperature and vibration sensors are widely implemented in predictive maintenance, while vision-based sensors contribute to defect detection and automation. Advances in wireless communication and IoT frameworks have further expanded the role of sensors, allowing real-time data sharing across decentralized manufacturing networks. These capabilities are essential for building adaptive, flexible, and efficient systems that reflect the vision of Industry 4.0.

2.2 Industry 5.0 and the Role of Sensors

While Industry 4.0 emphasizes automation and connectivity, Industry 5.0 shifts attention toward human-centric and sustainable innovation. In this context, sensors play a dual role: they continue to provide data for intelligent systems while also supporting technologies that enhance collaboration between humans and machines. Wearable devices, for instance, monitor worker health and ergonomics, creating safer environments and reducing risks during industrial operations. Environmental sensors are also essential in Industry 5.0, ensuring that sustainable practices are measurable and verifiable.

Another dimension of Industry 5.0 is personalization in manufacturing. Sensors embedded in production systems enable products to be customized according to specific user needs, while maintaining efficiency and quality standards. This creates opportunities for industries to move beyond mass production and deliver value-added, consumer-focused solutions.

2.3 Future of Industry 5.0

The future development of Industry 5.0 will likely depend on deeper integration of AI, edge computing, and advanced communication infrastructures. Sensors will remain the core enablers of these technologies, offering the data streams required for rapid decision-making and system adaptation. The ability of sensors to function reliably in diverse and dynamic environments will determine the extent to which industries can achieve resilience, sustainability, and personalization.

Emerging research also suggests that Industry 5.0 will promote new forms of cooperation between humans and intelligent systems, where sensor data provides the link between decision-making at the machine level and oversight by human operators. Furthermore, the combination of affordable sensors with high-end systems could make advanced industrial capabilities more widely accessible, reducing barriers for smaller organizations and fostering inclusive digital transformation.

Table 1 presents a comparative overview of Industry 4.0 and Industry 5.0, highlighting their core differences in automation level, human involvement, technologies, sustainability focus, and customization. Industry 4.0 is characterized by fully automated processes with minimal human intervention, relying heavily on AI, IoT, CPS, and robotics, whereas Industry 5.0 emphasizes human-centered automation supported by machines, collaborative robots, and sustainable sensor technologies. Table 1 also shows that Industry 5.0 integrates eco-friendly practices and personalized manufacturing, while Industry 4.0 remains oriented towards standardized mass production and higher energy consumption.

Table 1
A Comparative Analysis of Industry 5.0 vs. Industry 4.0

Feature	Industry 4.0	Industry 5.0
Automation level	Fully automated, minimal human intervention	Human-centered automation with machine support
Human involvement	Reduced to supervisory roles	Active collaboration with machines
Primary technologies	AI, IoT, CPS, robotics	Cobots, AI, sustainable sensors, edge computing
Sustainability focus	High energy consumption, automation-focused	Energy-efficient, circular economy approach
Customization	Standardized mass production	Personalized and adaptive manufacturing

2.4 Low-Cost Sensors: Applications, Benefits, and Challenges

Affordable sensor technologies are gaining widespread use in industrial and environmental domains as practical tools for continuous monitoring. Their most common areas of application include:

i. *air quality monitoring* – measuring concentrations of carbon dioxide, particulate matter (PM2.5), and other harmful gases to support the development of smart and sustainable cities;

ii. *temperature and humidity control* – applied in agriculture, food storage, and climate management systems such as heating, ventilation, and air conditioning;

iii. *vibration and acoustic detection* – implemented in predictive maintenance to identify irregularities and early-stage faults in industrial machinery;

iv. *wireless IoT solutions* – enable remote supervision of water levels, weather dynamics, and diverse industrial processes through networked, low-power devices.

Table 2 compares the technological workflows of Industry 4.0, Industry 5.0, and low-cost sensor systems, outlining their main process stages from data collection to decision-making. Industry 4.0 follows a highly automated, data-driven workflow supported by IoT devices, cloud computing, and AI analytics. Industry 5.0 builds on this structure but incorporates human–machine collaboration and sustainability checkpoints at each stage, ensuring ethical and environmentally conscious outcomes. Low-cost sensor systems maintain a simplified workflow focused on affordability and essential functionality, often using localized data processing and limited automation to meet budget and accessibility constraints.

Table 2
Benefits and limitations of low-cost sensors

Advantages	Challenges
Affordable and scalable	Lower accuracy and precision
Easy integration with IoT	Susceptible to environmental noise
Real-time data monitoring	Frequent recalibration required
Supports sustainability initiatives	Shorter lifespan compared to industrial sensors
AI-driven calibration improvements	Security vulnerabilities in wireless networks

Table 3 outlines the key advantages and limitations of Industry 4.0, Industry 5.0, and low-cost sensor systems. Industry 4.0 offers high efficiency, real-time monitoring, and advanced automation, but it requires substantial investment and can face cybersecurity vulnerabilities. Industry 5.0 adds value through human–machine collaboration, personalization, and sustainability, yet it may involve

higher operational complexity and slower implementation. Low-cost sensor systems provide affordability, ease of deployment, and accessibility for smaller enterprises, though they may have reduced accuracy, shorter lifespan, and limited integration capabilities compared to advanced industrial solutions.

Table 3
Sensor comparison in Industry 4.0, Industry 5.0, and low-cost sensors

Feature	Industry 4.0 sensors	Industry 5.0 sensors	Low-cost sensors
Primary use	Smart automation and real-time data	Human-machine collaboration and sustainability	Cost-effective monitoring
Technologies	IoT, CPS, AI analytics	AI, cobots, edge AI	IoT, wireless networks, cloud
Precision	High	High	Medium
Cost	Expensive	Expensive	Affordable
Sustainability	Energy-intensive	Eco-friendly design	Moderate impact
Challenges	Cybersecurity, cost barriers	Human-machine integration complexity	Accuracy, lifespan, and security issues

3. Comparative Analysis and Performance Evaluation

The transition from Industry 4.0 to Industry 5.0 has introduced significant shifts in the role of sensors, the scope of automation, and the interaction between humans and intelligent systems. This section offers a comparative perspective on Industry 4.0, Industry 5.0, and low-cost sensing solutions. The analysis highlights their main characteristics, areas of application, advantages, challenges, and contributions to sustainable practices. It also incorporates an evaluative approach to examine how sensors perform in terms of efficiency, accuracy, and adaptability across different industrial contexts.

Advancements in sensor technologies have been instrumental in driving the evolution of industrial systems. Within Industry 4.0, sensors primarily serve to automate processes, enable real-time monitoring, and generate data for informed decision-making, with the overarching aim of increasing productivity and optimizing operations. Industry 5.0, by contrast, builds upon these foundations but places greater emphasis on collaboration between people and machines, prioritizing sustainable methods and adaptive production strategies that complement human creativity.

At the same time, low-cost sensors offer affordable alternatives that extend digital monitoring to broader domains such as environmental assessment, predictive maintenance, and IoT-based solutions. However, their limited precision and consistency remain key obstacles to widespread adoption.

Table 4 presents a comparative analysis of the application areas for Industry 4.0, Industry 5.0, and low-cost sensor systems. Industry 4.0 applications are concentrated in fully automated manufacturing, predictive maintenance, smart logistics, and large-scale industrial monitoring.

Industry 5.0 builds upon earlier advances by placing human knowledge and creativity at the center of digitalized production. This approach supports personalized manufacturing, promotes sustainable use of resources, and encourages practices that are socially responsible. In parallel, low-cost sensor technologies are frequently adopted in budget-sensitive areas such as small-scale production, environmental monitoring, and infrastructure management. Their value lies in providing affordable and rapidly deployable solutions, even though they may lack the sophistication of high-end automated systems.

In contrast, Industry 4.0 relies heavily on sensors designed for autonomous production with limited human intervention. By combining AI, the Internet of Things, and cyber-physical systems, these technologies strengthen decision-making processes, reduce the likelihood of human error, and increase the efficiency of industrial operations. However, this model has also raised concerns, including the risk of workforce displacement, challenges in adapting to unexpected conditions, and

vulnerabilities linked to cybersecurity.

Table 4
Comparative analysis of sensors in Industry 4.0, Industry 5.0, and low-cost sensors

Feature	Industry 4.0 sensors	Industry 5.0 sensors	Low-cost sensors
Automation level	Fully autonomous, IoT-driven	Human-machine collaboration with AI integration	Limited automation, primarily IoT-based
Human involvement	Minimal supervision, machine-led decision-making	Workers and cobots collaborate actively	Requires manual calibration and supervision
Primary technologies	AI, IoT, CPS, digital twins	AI, cobots, smart sensors, edge computing	IoT, Wireless Networks, Cloud
Sustainability	High energy consumption, process optimization	Eco-friendly, resource-efficient production	Moderate sustainability impact
Customization	Standardized mass production	Personalized, adaptive manufacturing	Limited personalization
Cost	High initial investment, long-term ROI	High but balanced with human efficiency	Low-cost, scalable
Challenges	Cybersecurity, implementation costs	Human-robot integration complexity	Accuracy, durability, security concerns

Industry 5.0 addresses these challenges through the use of collaborative robots and intelligent decision-support tools, allowing human operators to work alongside automation while maintaining flexibility in customized production and advancing sustainable objectives. Low-cost sensors, although less accurate than advanced industrial devices, provide affordable and scalable solutions for real-time monitoring in areas such as IoT systems and smart urban infrastructure. Their limitations, however, include the need for frequent recalibration and sensitivity to environmental conditions, which restrict their reliability in sectors where high precision is essential, such as aerospace and advanced manufacturing.

3.1 Performance Evaluation of Sensors in Industry 4.0, Industry 5.0, and Low-Cost Sensors
3.1.1 Accuracy and Precision

Accuracy and precision play a vital role in industrial automation, safety monitoring, and predictive maintenance. With the advent of AI-driven calibration and real-time analytics, sensors in Industry 4.0 and Industry 5.0 have achieved high levels of precision. In contrast, low-cost sensors often struggle with maintaining consistent data.

Table 5 compares the cost implications of adopting Industry 4.0, Industry 5.0, and low-cost sensor systems. Industry 4.0 involves high initial investment due to advanced automation technologies, integration of IoT networks, and AI-driven analytics, but offers long-term efficiency gains. Industry 5.0 requires similar or slightly higher costs when incorporating collaborative robotics, sustainability measures, and customization features, which can increase implementation expenses. Low-cost sensor systems have minimal upfront and maintenance costs, making them suitable for smaller enterprises or projects with budget constraints, though their limited functionality may restrict long-term scalability and performance.

Table 5
Accuracy and precision comparison of sensors

Sensor type	Accuracy (%)	Precision
AI-powered smart sensors (Industry 4.0)	98-99	High
Cobotic sensors (Industry 5.0)	97-99	High
Low-cost IoT sensors	85-92	Moderate

3.1.2 Energy Efficiency and Sustainability

Industry 5.0 sensors focus on sustainability by minimizing energy waste, whereas Industry 4.0 sensors continue to depend on significant power consumption for automation. Table 6 highlights the sustainability aspects of Industry 4.0, Industry 5.0, and low-cost sensor systems.

Table 6
Energy consumption and sustainability performance

Sensor type	Energy consumption	Sustainability index
Industry 4.0 sensors	High (24/7 operation)	Moderate
Industry 5.0 sensors	Moderate (AI-driven)	High
Low-cost sensors	Low (battery-operated)	Low-Moderate

Industry 4.0 contributes to sustainability through optimized resource use, energy efficiency, and reduced waste via predictive analytics, although its high energy demand for large-scale automation can offset some benefits. Industry 5.0 strengthens the sustainability dimension by integrating circular economy principles, eco-friendly materials, and human oversight to ensure environmentally and socially responsible production. Low-cost sensor systems support sustainability by enabling affordable environmental monitoring and efficient resource management, yet their shorter lifespan and potential for higher replacement rates can present environmental challenges.

3.1.3 Workflow of Sensor Functionality in Industry 4.0 and Industry 5.0

Workflow stages of sensors in Industry 4.0 and 5.0 are:

i. *data collection* – sensors gather data related to machines, the environment, and human interactions;

ii. *data transmission* – IoT networks, edge computing, and wireless connections transmit the data collected by sensors;

iii. *AI processing & decision making* – AI algorithms process the data to facilitate predictive maintenance and real-time monitoring;

iv. *actuation and feedback* – machines and collaborative robots (cobots) perform tasks based on insights derived from AI;

v. *continuous learning & optimization* – adaptive learning models enhance efficiency over time.

Figure 1 illustrates the operational workflow of intelligent sensor-based systems, showing the sequential process from data acquisition to system optimization. The cycle begins with data collection, where sensors capture relevant environmental or operational parameters. This information is then sent through data transmission channels to processing units.

In AI processing and decision making, algorithms analyse the data and generate actionable insights. These insights drive actuation and feedback, where control actions are executed, and responses are monitored. Finally, continuous learning and optimization uses accumulated data and

performance outcomes to refine system behaviour over time, ensuring improved accuracy, adaptability, and efficiency.
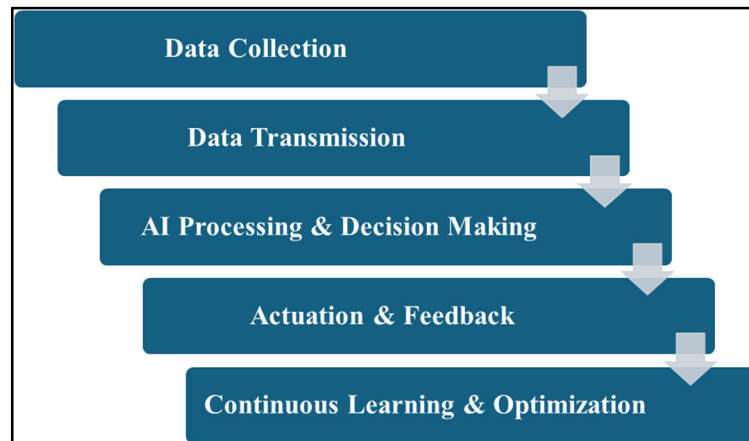

Fig. 1. Workflow of Sensors in Industry 4.0 and Industry 5.0

3.1.4 Workflow of Low-Cost Sensors

Workflow stages of low-cost sensors are:

i. *data collection* – low-cost sensors collect environmental, mechanical, or operational data, including temperature, humidity, vibration, and air quality;

ii. *data transmission* – the collected data is transmitted via wireless communication protocols such as Wi-Fi, LoRaWAN, Bluetooth, or NB-IoT to cloud servers or local processing units;

iii. *data processing & analysis* – cloud-based analytics, edge computing, or onboard microcontrollers process sensor data to detect patterns and anomalies;

iv. *decision making & actuation* – based on processed data, automated systems trigger actions such as maintenance alerts, energy optimizations, or adjustments;

v. *feedback & calibration* – periodic recalibration and AI-driven learning mechanisms improve sensor accuracy and long-term reliability.

Figure 2 depicts the functional workflow of low-cost sensor systems, outlining the stages from initial data acquisition to system calibration. The process begins with data collection, where sensors capture physical or environmental parameters. This is followed by data transmission, in which collected data is sent to processing units through wired or wireless channels. In data processing and analysis, the information is evaluated to extract meaningful insights. Decision making and actuation then apply these insights to initiate appropriate actions. The final stage, feedback and calibration, ensures the system remains accurate by adjusting sensor performance and operational parameters based on observed outcomes.

3.2 Future Directions and Challenges

The use of sensors within Industry 4.0, Industry 5.0, and cost-effective monitoring platforms has significantly transformed automation, sustainable practices, and real-time industrial oversight. Despite these advances, there are still persistent challenges and open research questions that must be addressed before these systems can achieve widespread implementation and seamless integration.
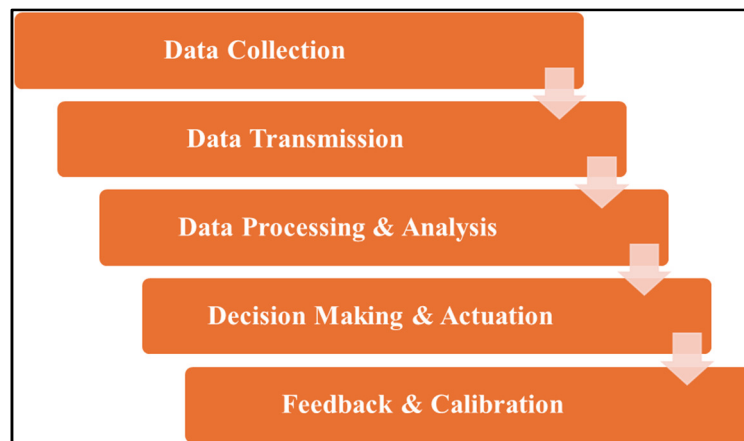
Fig. 2. Workflow of low-cost sensors

3.2.1 Accuracy and Calibration Issues

Maintaining precision in dynamic environments remains one of the most pressing challenges for sensor technologies across Industry 4.0, Industry 5.0, and low-cost applications:

i. *Industry 4.0* – high levels of accuracy are essential to support automated processes. Even minor calibration errors can disrupt operations, compromise data analytics, and lead to costly downtime;

ii. *Industry 5.0* – in contexts where humans and robots work together, real-time accuracy becomes even more critical to guarantee both safety and efficiency during collaborative tasks;

iii. *low-cost sensors* – affordable devices are particularly vulnerable to problems such as data drift, external interference, and performance degradation, making frequent recalibration necessary to maintain dependable results.

Future research directions related to the accuracy and calibration issues are:

i. advancing AI-based self-calibration techniques that allow sensors to maintain accuracy in dynamic and unpredictable industrial environments;

ii. investigating sensor fusion approaches that combine data from multiple sensing devices to achieve higher precision and reliability;

iii. designing automated recalibration frameworks supported by machine learning models, enabling real-time detection and correction of measurement errors;

3.2.2 Cybersecurity and Data Privacy Risks

As sensor networks increasingly rely on IoT platforms, cloud infrastructures, and wireless communication, cybersecurity concerns have become more prominent:

i. *Industry 4.0* – the dependence on cloud-based analytics exposes systems to risks such as hacking attempts, data breaches, and targeted cyberattacks;

ii. *Industry 5.0* – closer integration between humans and machines introduces additional vulnerabilities, particularly relating to privacy protection and unauthorized system access;

iii. *low-cost sensors* – devices deployed in open or remote environments are especially at risk, as they can be exploited through data interception, unauthorized entry, or manipulation of transmitted signals.

Future research directions related to cybersecurity and data privacy risks are:

i.   implementing blockchain technology to ensure the integrity of sensor data and improve authentication processes;
ii. developing AI-driven anomaly detection systems to mitigate cyber threats and unauthorized access;
iii. creating encryption methods and secure IoT frameworks to bolster data privacy and enhance the security of sensor communications;

3.2.3 Energy Consumption and Sustainability Concerns

With sustainability goals gaining greater importance, sensor systems must be designed to minimize energy use while maintaining reliable performance:

i. *Industry 4.0* – sensors often consume substantial amounts of power since they operate continuously to support real-time monitoring and automated decision-making;
ii. *Industry 5.0* – while promoting environmentally conscious manufacturing, these systems still require advanced energy management strategies to balance operational efficiency with sustainable practices.

Future research directions related to energy consumption and sustainability concerns are:

i.   creating energy-harvesting sensors that utilize solar, thermal, and kinetic energy sources;
ii. developing ultra-low-power AI chips tailored for edge computing applications, which will lower energy consumption while ensuring efficiency;
iii. combining self-powered wireless sensors with energy-efficient IoT frameworks to facilitate sustainable monitoring applications.

3.2.4 Standardization and Interoperability Issues

One of the persistent difficulties in sensor technology is ensuring seamless interoperability across diverse industrial platforms:

i.   *Industry 4.0* – sensors often operate on multiple communication protocols, making system integration complex and potentially increasing implementation costs;
ii. *Industry 5.0* – effective collaboration between humans and robots requires real-time data exchange, which depends on smooth cross-platform integration of sensor networks;
iii. *low-cost sensors* – the absence of standardized frameworks frequently leads to compatibility issues when these devices are connected with industrial-grade IoT infrastructures.

Future research directions related to energy consumption and sustainability concerns are:

i.   creating global IoT communication standards to ensure sensor data interoperability across different industries;
ii. developing open-source frameworks for sensor integration to improve compatibility among Industry 4.0, Industry 5.0, and low-cost sensor networks;
iii. implementing AI-driven middleware solutions that can translate and optimize sensor data from various protocols for effective communication.

3.2.5 Future Prospects: AI-Driven Predictive Maintenance and Smart Sensors

The future progress of sensors in Industry 4.0 and Industry 5.0 is closely tied to the integration of AI, particularly in predictive maintenance aimed at improving equipment reliability and preventing unexpected failures:

i.   *Industry 4.0* – AI-enabled sensors can detect anomalies in real time, anticipate potential breakdowns, and trigger preventive actions that reduce downtime and increase operational efficiency;
ii. *Industry 5.0* – Smart sensors will evolve further by embedding adaptive learning models, allowing them to dynamically respond to human interactions and environmental variations;
iii. *low-cost sensors* – Even cost-effective devices are expected to benefit from AI-driven cloud platforms, which can compensate for accuracy limitations and provide improved decision support in smart environments.

3.2.6 Future Prospects: Edge Computing and Real-Time Processing

The integration of edge computing is expected to play a crucial role in reducing latency, strengthening real-time decision-making, and improving the efficiency of sensor data processing:

i.   *Industry 4.0* – reliance on centralized cloud platforms often introduces delays that can disrupt operations in high-speed industrial environments;
ii. *Industry 5.0* – by incorporating edge AI computing, decisions can be made directly on the production floor, allowing immediate responses based on sensor inputs;
iii. *low-cost sensors* – deployments in remote or resource-limited areas will particularly benefit from localized edge processing, which decreases dependence on cloud connectivity and ensures more reliable data handling.

3.2.7 Future Prospects: Integration of Digital Twins in Industry 5.0

The integration of Digital Twin technology in Industry 5.0 will significantly improve sensor-based predictive analytics and process optimization by creating virtual replicas of physical assets:

i.   While Industry 4.0 has already implemented digital twins for predictive maintenance and simulation-based optimization.
ii. Industry 5.0 aims to enhance these capabilities by focusing on human-centric automation, promoting a smooth collaboration between workers and machines.
iii. Additionally, affordable sensor systems can utilize digital twins for environmental forecasting and extensive urban planning.

Table 7 summarizes the future directions and research opportunities for Industry 4.0, Industry 5.0, and low-cost sensor systems. Industry 4.0 research is expected to focus on enhancing AI-driven decision-making, strengthening cybersecurity, and improving interoperability between diverse industrial systems. Industry 5.0 will likely advance in developing adaptive human–machine collaboration models, integrating sustainability metrics into production workflows, and promoting socially responsible innovation. Low-cost sensor systems present opportunities for improving accuracy, durability, and connectivity while maintaining affordability, enabling broader adoption in developing regions and resource-limited industries.

Table 7
Future trends in sensor technology development

Emerging technology	Expected impact	Application
AI-enhanced smart sensors	Improved decision-making and predictive analytics	Industry 4.0, Industry 5.0
Blockchain for sensor security	Secure data transactions and authentication	Industry 4.0, Industry 5.0, low-cost IoT
Energy-harvesting sensors	Self-powered, eco-friendly operation	Low-cost sensors, smart cities
Edge AI computing	Real-time data processing at the source	Industry 4.0, Industry 5.0, remote IoT applications
Digital twin integration	Improved simulation, predictive maintenance	Industry 4.0, Industry 5.0

4. Conclusion

The analysis presented in this study demonstrated that sensor technologies remain a cornerstone of industrial transformation. Industry 4.0 established the foundations of digitalized production by embedding intelligent sensors into interconnected systems, enabling automation, predictive maintenance, and advanced data-driven decision-making. Industry 5.0 expanded on this framework by restoring a central role for human creativity, emphasizing sustainable practices, and building resilient production environments. In parallel, the spread of low-cost sensors has made digital monitoring and control more accessible, particularly for organizations with limited resources.

A comparison of these three domains showed that while high-end industrial sensors delivered accuracy and reliability, low-cost alternatives provided broader inclusivity by reducing the entry barriers to digital transformation. Their combination within Industry 4.0 and Industry 5.0 environments creates opportunities for balanced systems that are efficient, sustainable, and adaptable.

Looking ahead, the integration of AI, edge computing, and real-time data processing will further strengthen the value of sensors in both advanced and resource-constrained industries. These technologies are likely to support faster adaptation to changing environments, more effective predictive capabilities, and improved decision-making at all levels of production. At the same time, continued research into energy efficiency, interoperability, and resilience will be essential for unlocking the full potential of sensor-based industrial systems.

In conclusion, sensors serve not only as instruments of measurement but also as enablers of strategic transformation. Their role in Industry 4.0, Industry 5.0, and affordable monitoring solutions illustrates the diverse pathways through which industries can progress toward smarter, greener, and more human-centered production models.

Conflicts of Interest
The author declares no conflicts of interest.

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