Industry 5.0

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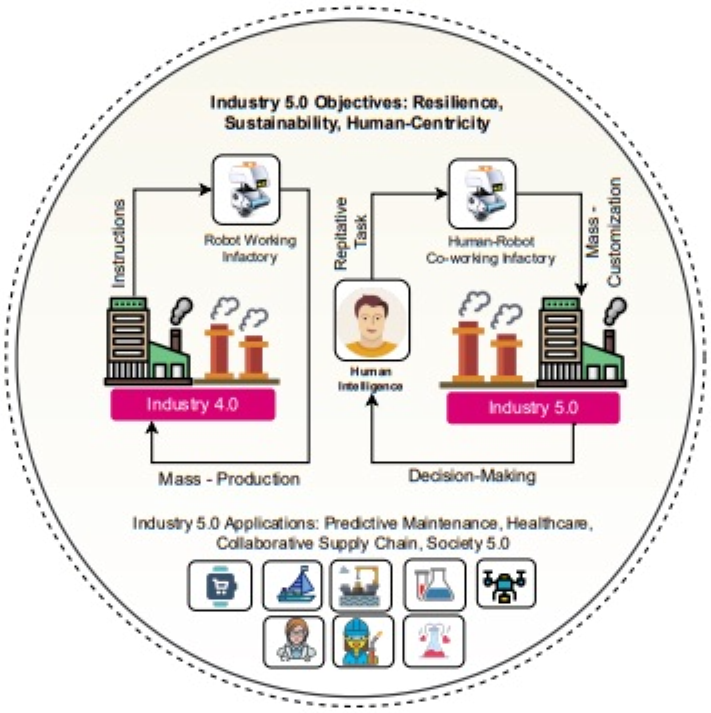

Fig. 1. Concept of Industry 5.0.

I. INTRODUCTION

CURRENT industrial revolution, *i.e.*, Industry 4.0, has prompted the automation of industrial processes and the integration of critical technologies such as edge computing, cloud computing, IoT, and AI to achieve the vision of intelligent factories and enhance production [1]. It primarily aims to increase productivity and mass customization, transforming previous versions. Throughout the 1800s, Industry 1.0 developed by creating mechanical manufacturing infrastructures for water and steam-powered machines. The introduction of electric power and assembly line manufacturing marked the beginning of Industry 2.0 in 1870 as production capacity rose and the economy greatly benefited. In Industry 2.0, mass production and workload allocation play a significant role in boosting the productivity of manufacturing firms. As a result of the second industrial revolution, environmental pollution increased significantly throughout the world. Industry 3.0, the third industrial development, is frequently associated with computer technology, automation, transportation, and logistics development. As a result of Industry 3.0, manufacturing and production processes have significantly improved efficiency, precision, and personalization. Later, in 2011, smart manufacturing for the future evolved into Industry 4.0 [2]. Aside from enhancing productivity and mass production, the basic goal of Industry 4.0 is to harness the power of emerging technology [3]. Industry 5.0 is the forthcoming industrial revolution, a cognitive control process based on Industry 4.0, where human-machine interactions are enhanced. This would result in a value-driven rather than a process-driven approach.

In Industry 5.0, AI would combine human experience with cognitive abilities and precision control. Fig 1 illustrates the key concepts behind the Industry 5.0 revolution. Industry 5.0 is envisioned to improve production quality by delegating repetitive and uninteresting tasks to robots while humans manage critical reasoning and intelligent duties. This would create a demand for skilled personnel [4]. Since humans fully understand and can work with robotic colleagues, they can coexist in the workplace without fear or apprehension. As a result, production processes will be incredibly effective and value-added, trustworthy autonomy will flourish, waste will disappear, and associated costs will be lower [5].

Furthermore, this phase focuses on intelligent, linked, and autonomous systems that function efficiently and adapt to changing conditions [1], [6]. On the other hand, edge computing is essential for these systems to operate in real-time, with minimal latency and outstanding reliability. One of the essential advantages of edge computing is the capacity to handle and industrial analyse data in real time. As Industry 5.0 develops, intelligent systems must be able to modify their response quickly based on real-time data and make decisions in real-time. For example, edge computing can be used in a manufacturing plant to analyse real-time sensor data from production equipment. It can minimise downtime and increase efficiency by detecting potential problems and enabling predictive maintenance.

Self-driving automobiles, autonomous robots, data from innovative equipment, and automated retail are examples of edge use cases [7].

II. The Potential of Industry 5.0

Industry 5.0 has vast potential, marking a fundamental shift in our perception of the link between technology and work. It has the potential to generate creative forms of employment that are more fulfilling and meaningful. It also enhances productivity and efficiency by concentrating on human needs and capabilities. Edge Computing involves the processing and analysis near the data source. This approach minimises delays and eliminates the requirement for significant data transmission to centralised servers. It plays a crucial role in Industry 5.0 by enabling the implementation of AI algorithms and models at the edge, enabling real-time data processing and lowering dependence on cloud-based computing. Moreover, it facilitates expedited response times, heightened security, and greater bandwidth optimisation through localised data processing on edge devices or servers. Mattila *et al.* [8] have discussed an in-depth study of Industry 5.0, including its integration with IoT, AI, and big data. On the other hand, Javaid *et al.* [9] have discussed the use of Industry 5.0 to offer personalized therapy and patient diagnosis for Coronavirus disease (COVID). They deployed Industry 5.0 technology (such as humanoid robots, telemedicine, holography, 4D scans, and intelligent inhalers) to combat the COVID-19 pandemic. According to a survey, Elfar *et al.* [10] have discussed the perspective of Industry 5.0 in algal biorefineries can customise algae creation and enable real-time algae growth monitoring, lowering operational expenses. This study Javaid *et al.* [11] demonstrates that Industry 5.0 would retain a favourable environmental impact while not damaging marine resources by properly deploying AI models.

A. Limitation of Traditional Industry: Why Industry 5.0?

Traditional industries have strict organisational structures and processes, which might limit their capacity to adjust swiftly to market changes or integrate emerging technologies, which results in limited flexibility. A lack of innovation and competitiveness is caused by traditional industries relying on tried-and-true strategies rather than adopting new ideas. Often, they require substantial capital investments in equipment and infrastructure, which may prevent new businesses from entering the market. Traditional industries can have a significant environmental impact as they rely on fossil fuels and non-renewable resources. They might have opaque supply chains or manufacturing methods, and consumers may need help understanding the sources and quality of the products they purchase. Traditional industries frequently depend on centralised decision-making procedures. Such circumstances can result in delays in addressing alterations or interruptions, constraining the system's ability to adjust. Industry 5.0 implements a system of decentralised decision-making through the utilisation of edge computing. Edge computing allows for rapid responses to dynamic environments, enhancing the agility and adaptability of systems. On the one hand, traditional industries encounter difficulties adjusting to evolving market requirements or unexpected disruptions due to inflexible procedures and structures. On the other hand, Industry 5.0 prioritises the use of flexible and responsive systems with the help of edge computing, which these goals facilitate rapid adaptation of industrial processes, allocation of resources, and decision-making in response to dynamic conditions. Future industries must be functional in solving pressing societal concerns [12]. For *e.g.*,

I) Circular production models, emerging enabling ICT technologies, and revision of energy consumption policies for efficient utilisation of natural resources in the event of external shocks, such as the COVID-19 pandemic (resiliency).
II) Environmental and natural resource preservation and climate change (sustainability).
III) Digital hyperconnectivity and evolving digital skills for people empowerment and social stability (human-centric). Industry 5.0 vision components must realise and enable the 17 Sustainable Development Goals (SDG) or goals defined in the United Nations (UN) agenda 2030.

B. Evolution Matrix of Industry 5.0

The Industry 5.0 evolution matrix shows a roadmap of how the manufacturing sector will likely change over time, considering numerous technological advancements and innovations. These matrices included content delivery, production cost, resource management, quality control, technological advancement, human-machine collaboration, personalisation and customisation. It emphasises the need for scalable solutions to support the growth and expansion of industrial processes. This is especially crucial as businesses increasingly use digital technologies to optimise operations and boost productivity.

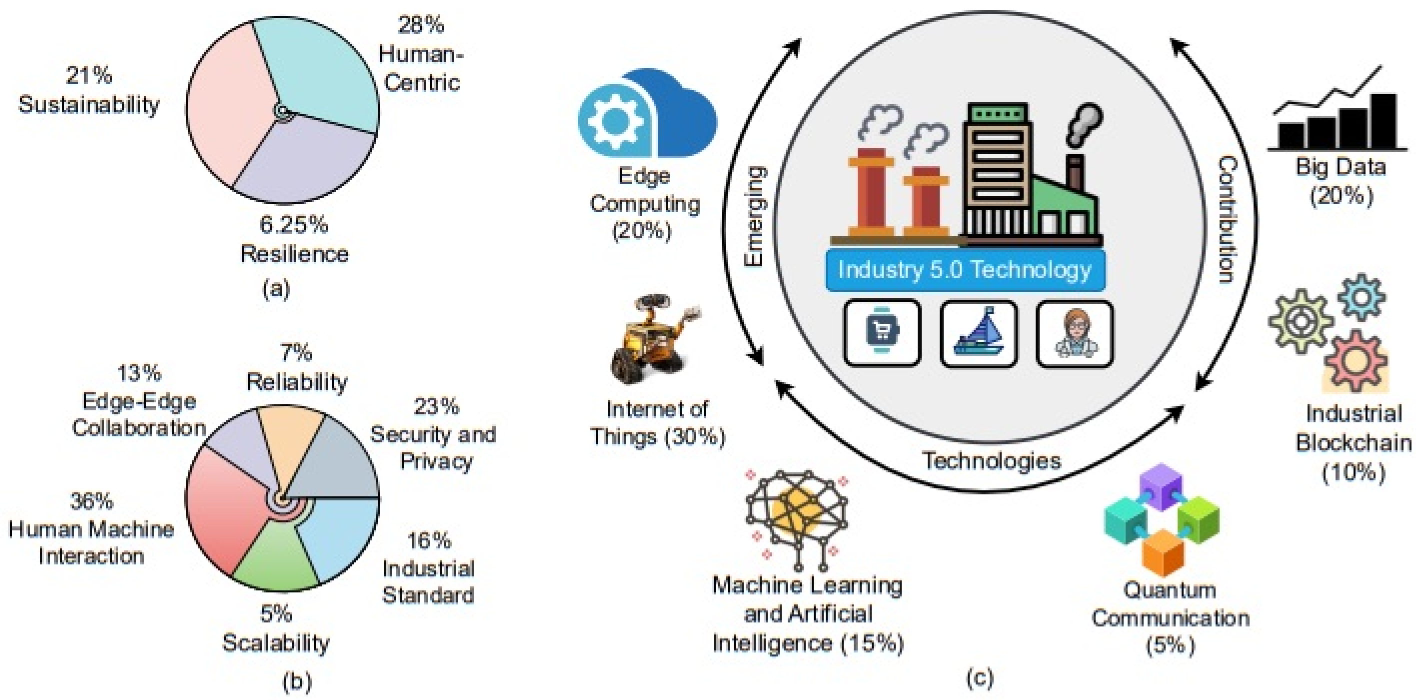

Fig. 2. Literature analysis on Industry 5.0 edge computing-based study. (a) Contributions to objective-specific Industry 5.0, (b) Domain-specific contributions, (c) Contribution of cutting-edge technologies.

The matrix emphasises adopting technologies that scale sustainably and efficiently to enable industrial development. This includes creating technology to monitor and optimise various operations, such as manufacturing, shipping, and supply chain management. It also involves implementing technologies that allow industrial equipment to be monitored and controlled remotely, increasing efficiency and flexibility. Industry 5.0 will integrate sophisticated technologies such as AI, robotics, and IoT to develop more collaborative and sustainable work environments that use human and machine strengths. We should expect to see the rise of cutting-edge technology and novel methods of industrial development that value both people's and the environment's well-being. Furthermore, Fig. 3 shows an overview of the evolution of Industry 5.0.

C. Key Feature of Edge Computing in Industry 5.0

Industry 5.0 is a manufacturing vision for the future that builds on earlier industrial revolutions while embracing modern technologies and human-centric techniques to produce a more sustainable, efficient, and flexible manufacturing ecosystem [5]. Among the primary elements of Industry 5.0 are:

1) Human-Machine Collaboration: Rather than replacing humans with automation, Industry 5.0 emphasises the necessity of synergy between humans and machines. This strategy recognises human worker's unique skills to think creatively, solve issues, and judge while harnessing machine speed and precision. Edge computing provides various advantages, such as decreased bandwidth consumption, improved data privacy and security, offline functionality, and quicker response times. This enables immediate decision-making and empowers edge devices to react promptly to critical events, reducing latency and enhancing operational efficiency.
2) Advanced Technologies: Industry 5.0 enables real-time monitoring, analysis, and optimisation of production processes by utilising cutting-edge technologies like ML, AI, robotics, edge computing and the IoT. Maintenance prediction, quality control, and supply chain management are also possible with these technologies.
3) Sustainability: Industry 5.0 emphasises the importance of environmental effects and sustainability in manufacturing. This involves using renewable energy sources, reducing waste, and developing sustainable materials and goods. Edge computing improves sustainability by decreasing data transport and promoting immediate decision-making, optimising resource utilisation and minimising environmental consequences.
4) Cybersecurity and Data Privacy: Industry 5.0 recognises the need for cybersecurity and data privacy in manufacturing, particularly as more industrial processes become internet-connected. Such measures include secure data transfer, encryption, and access control. Incorporating edge computing strengthens cybersecurity by locally processing sensitive data, minimising vulnerability to centralised attacks, and improving data privacy through distributed storage, minimising the dangers associated with large-scale data breaches.
5) Customization & Personalization: Industry 5.0 enables widespread product customisation through digital design tools, flexible manufacturing processes, and enhanced supply chain management systems. This allows the mass creation of highly personalised products while maintaining efficiency and quality. Moreover, by providing up-to-date information and personalised interactions, edge computing improves the ability to customise and offer products or services, increasing user satisfaction and operational efficiency.

D. How Edge Computing Works in Industry 5.0?

In Industry 5.0, edge computing has advanced to facilitate the implementation of AI algorithms and models at the edge. This allows for immediate data processing and decreases the

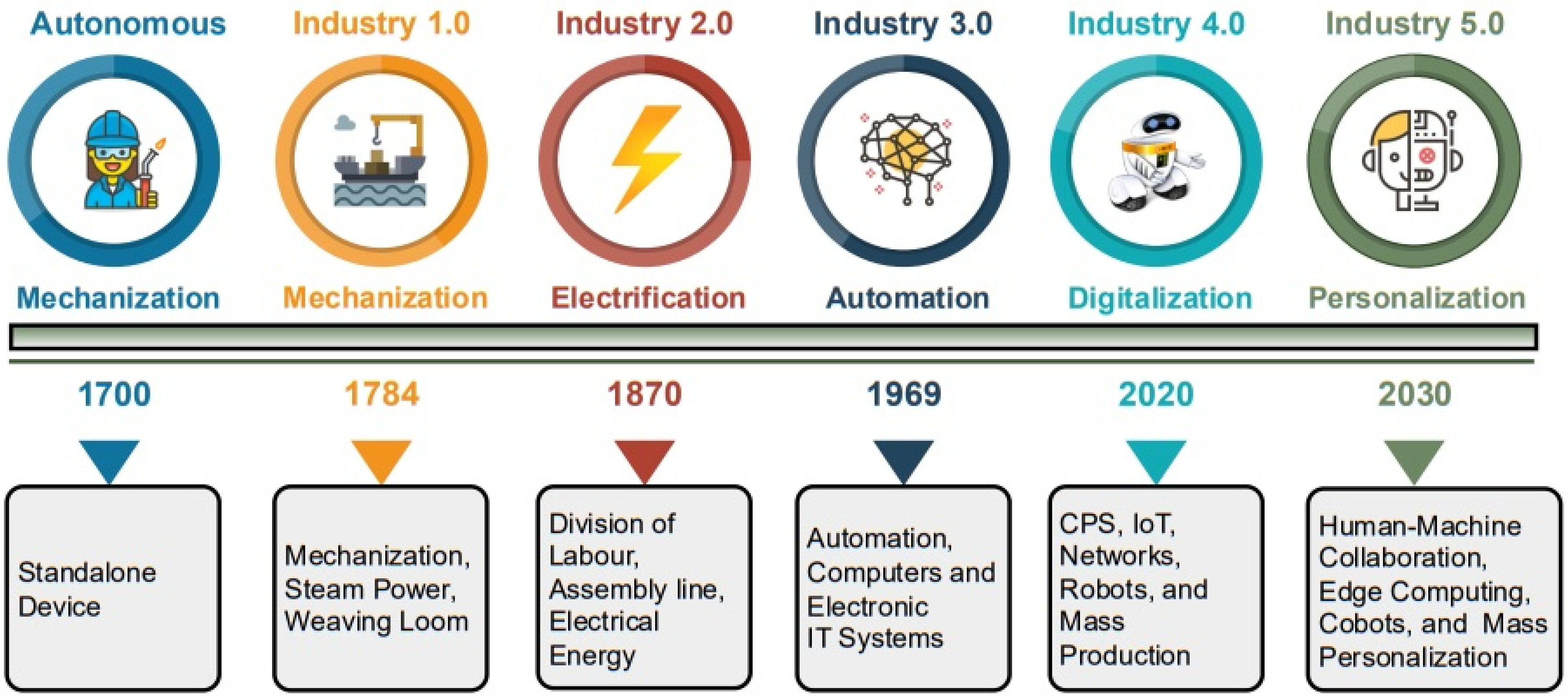

Fig. 3. Illustration of industrial revolutions and considered technologies.

TABLE I
EDGE COMPUTING IN INDUSTRY 4.0 AND INDUSTRY 5.0

Edge-based Parameters	In Industry 4.0	In Industry 5.0
Customization	Low	High
Latency Concern	Moderate	High
Interconnectivity	Moderate	High
Security Concern	Moderate	High
Decision-Making	Low	High
Processing Power	Moderate	High
Sustainability	Low	High

need for cloud-based computing. This signifies a notable progression beyond prior industrial benchmarks, such as Industry 4.0 [13]. In Industry 4.0, edge computing was employed, but its significance was less prominent than in Industry 5.0. The emphasis was primarily on incorporating tangible resources with cutting-edge technology such as IoT, cloud computing, and big data analytics. In Industry 5.0, edge computing goes beyond decentralising decision-making processes, allowing for real-time decision-making, improving data privacy and security, and offering offline capabilities. The increasing adoption of edge computing in Industry 5.0 is motivated by the necessity for quicker response times, decreased latency, higher operational efficiency, and heightened security. These factors are crucial for the human-centric and highly interconnected nature of Industry 5.0 systems. Table I summarizes the evolution of edge computing in Industry 5.0 [14].

E. Difference Between Industry 5.0 and Other Revolutions

The phrase *Industry 5.0* was recently coined to define the latest stage in the growth of industrial technology. It began in the late 18th century with the introduction of mechanical power and resulted in significant changes in how we work and live. There have been multiple versions of the industrial revolution, each with technological advances and manufacturing process alterations. In the first industrial revolution, mechanical power was introduced, and the replacement of physical labour characterised this age. The manufacturing process became more standardised to boost efficiency, and assembly lines were implemented in Industry 2.0. The third industrial revolution, often known as Industry 3.0, began in the mid-20th century and lasted until the late 20th century. The current era is Industry 4.0, often called the fourth industrial revolution. It began in the early twenty-first century and is distinguished by incorporating digital technologies into production. Intelligent factories are highly automated and linked in this era.

Industry 5.0 is the ongoing development of the fourth industrial revolution. It is distinguished by incorporating both humans and machines into the manufacturing process. This epoch is dedicated to developing a more human-centred approach to manufacturing, in which machines and humans collaborate to manufacture items. This technique tries to blend mechanical efficiency and precision with human creativity and problem-solving abilities. Industry 5.0 strives to make production more sustainable and socially responsible, minimize waste and resource consumption and can be reused, recycled, or repurposed at the end of their lifecycle. The main key differences are summarized in Table II.

III. INDUSTRY 5.0 OBJECTIVES

Industry 5.0 emphasizes resilience, sustainability, and human-centricity. These characteristics are desirable and vital for the industry to remain relevant, competitive, and future-ready. That future may be nearer than many believe; in some ways, it may already be here. The digital revolution is well underway and shows no signs of abating. Industries must invest in technologies and employees to benefit from their

TABLE II
COMPARISON AMONG DIFFERENT INDUSTRIAL REVOLUTIONS

Parameters	Industry 1.0	Industry 2.0	Industry 3.0	Industry 4.0	Industry 5.0
Time Period	Late 18th to early 19th centuries	Late 19th century to early 20th century	Late 20th century to early 21st century	Early 21st century to present day	Future (Not yet established)
Key Technologies	Steam engine, Mechanization	Mass production & Assembly line	Automation, Digitization & Computers	IoT, AI, and Big Data	AI, Nanotechnology, and Renewable Energy
Production Focus	Automation of manufacturing processes	Standardized mass-production of goods	Personalization of commodities on a large scale	Manufacturing that is smart and linked	Production that is both sustainable and ethical
Human Role	Machine operators & labourers	Operators & assemblers can work	Employees who are problem solvers and innovators	Advanced AI, Replacing human	Collaboration between humans and machine
Communication	Telegraph, Telephone	Radio, & Television	Internet, Mobile Devices, Social Media	IIoT, Real-time data sharing and analysis	Intelligent communication and collaboration
Manufacturing scale	Large factories and Mills	Large factories and Assembly lines	Decentralized production, flexible manufacturing	Smart factories, DT, 3D printing	Distributed manufacturing and production networks
Production speed	Standardized production speed	High-speed production	Real-time production and delivery	Flexible and adaptive production processes	On-demand production and delivery
Supply Chain	Local supply chains	Linear supply chains	Networked supply chain with real-time monitoring	Agile and responsive supply chains	Decentralized and autonomous supply chains
Key Industry	Textile, Iron and Steel, mining	Automotive, Steel, & Chemicals	Electronics, IT, Biotechnology	Industry 4.0 technologies across industries	Industries across sectors

relative capabilities. More robust collaboration is required between businesses on the one hand and education and training institutions on the other, as companies are well placed to identify skill gaps and foresee future skill needs [15]. Industry 5.0 achieves productivity and human-centred outcomes using cobots, AR/VR, and flexible manufacturing systems while prioritising safety and working conditions.

Likewise, the industry can contribute to societal resilience by being robust, ensuring output is maintained and workers can continue working. It allows people empowerment (*i.e.*, digital society, workforce) in conjunction with mass-customization goals in optimized supply chains, *e.g.*, adaptability and scalable product varieties, resulting in positive impacts and benefits for various fields of society and bringing about the next industrial revolution.To enhance sustainability by establishing a more efficient and ecologically friendly manufacturing environment. To reduce waste and improve resource efficiency by embracing green technologies and sustainable practices. Therefore it is essential to discuss the objectives of Industry 5.0. Based on the existing literature, we can categorize the objectives of Industry 5.0 into three categories. These three fundamental objectives are resilience, sustainability, and human-centricity. The core values of Industry 5.0, as pictorially explained in Fig. 4.

A. Resilience

Resilience refers to the requirement to achieve a higher level of robustness in industrial production, equipping it better against disruptions and ensuring it can deliver and sustain critical infrastructure in times of crisis. System failures, cyber attacks, and supply chain disruptions make the manufacturing system more sensitive to disturbances. Hence, organisations must design resilience into their production systems to mitigate the impact of these interruptions and recover swiftly. Moreover, incorporating edge computing ensures that processing is distributed rather than centralized by processing data at the network's edge. By doing this, data processing is continued, even if one or more nodes fail. Conversely, sensitive data is kept closer to the user, reducing the risk of data breaches. On the other hand, AI systems can analyse massive volumes of data from numerous sources to discover potential dangers and vulnerabilities in industrial operations. It helps assess and predict risks by recognising patterns and correlations, enabling proactive risk management solutions to limit interruptions and assure business continuity. To implement resilience in Industry 5.0, organizations use various models and frameworks. One such model is the Resilience Engineering (RE) model, which provides a holistic approach to resilience and focuses on the interaction of humans, technology, and the environment. This model comprises four main components such as anticipation, monitoring, response and learning. Anticipation involves determining potential risks and preparing the organization to tackle them. The organization uses various tools such as risk assessments, scenario planning and simulation exercises to anticipate potential disruptions. Similarly, continuous monitoring of the system for changes and potential disruptions. Organizations can use various tools for monitoring, such as sensors, AI algorithms and data analytics, to detect changes and potential disruptions. Organizations can learn from previous events and improve their resilience by implementing post-incident analyses, feedback loops, and continuous improvement processes. Therefore, by implementing these technical tools and approaches within the RE model, organizations can build a resilient system that adapts and responds to disruptions in Industry 5.0 [5].

B. Sustainability

In Industry 5.0, sustainability refers to the ability of the production system to meet current demands without jeopardizing the ability of future generations to meet their own needs. This requires optimising the use of resources such as energy, water, and raw materials to reduce waste and lessen the environmental effect of manufacturing operations [16], resulting in an emphasis on circular economy practices and resource-efficient design. Furthermore, AI can monitor and assess environmental conditions by analysing data from sensors, satellites, and other sources. Industry 5.0 is the first industrial revolution led by humans based on the 6R (i.e. Reduce, Realize, Reuse, Recycle, Reconsider, and Recognize). It must establish circular methods for reusing, repurposing, and recycling natural resources, reducing waste and environmental impact, ultimately leading to a circular economy with improved resource efficiency and effectiveness. Incorporating edge computing contributes to sustainability by decreasing the need for large-scale data transfers to centralised data centres. Edge devices analyse and filter data locally, communicating only the essential insights rather than sending vast amounts of data across long distances. This method reduces network congestion, energy usage, and the carbon footprint associated with data transmission.

There are many practical scenarios where sustainability has been implemented successfully. Some manufacturers have switched to renewable energy sources such as solar and wind power for long-term development. Others have used closed-loop manufacturing systems to recycle waste materials into the manufacturing process, decreasing waste and conserving resources. Sustainable agriculture brings about resource conservation, environmental protection, and community support. Crop rotation, natural pest management, water conservation, and the usage of organic and locally sourced produce can all contribute to this. Others use conservation tillage practices such as no-till farming to limit soil erosion and water use. Several buildings now feature green roofs and rainwater collection systems to reduce water consumption. Passive heating and cooling techniques, such as natural ventilation and shading, are also used in some facilities to reduce energy use. By adopting sustainable practices, industries reduce their environmental impact, conserve resources, and improve their bottom line.

C. *Human-Centric*

Human centricity refers to developing products, services, and systems focusing on human needs and capabilities. This approach recognises that humans are the ultimate consumers of technology, and their requirements and preferences should be considered during the design process [17]. AI algorithms detect possible hazards, identify safety problems, and issue timely alerts or interventions. This proactive approach to safety decreases the likelihood of accidents and prioritises worker's physical and mental well-being. On the other hand, incorporating edge computing enables real-time interactions and personalised experiences in human-centric applications. The delay between data collection and action considerably decreases when edge devices execute data processing and analysis at the network edge. This near-instant response time improves user experiences in various disciplines, including smart homes, cities, and healthcare. For instance, in smart homes, edge devices may swiftly analyse sensor data to modify ambient settings, giving inhabitants personalised comfort.

HRC has been popular in the previous decade for improving the working conditions and reproducible quality of manual task [18]. One futuristic perspective is expedited by an Augmented Robot, Cognitive System, Mixed Reality and Co-Intelligence by four Enhanced Human Abilities (EHAs) to Energise, Advise, Support and Empower (EASE) a human operator physically and intellectually. With the thoughts-driven assistance of brain robotics and sensing-enabled context awareness, the super operator implements their knowledge to carry out a human-centric assembly task best [19].

- Augmented Robot: Due to fatigue, the human body has low and unsustainable muscle power over time. In contrast, weak muscles can be electrified by using an augmented robot, for instance, the exoskeleton with active and passive actuation. As a result, a human operator helped by an exoskeleton can execute long-term tasks beyond physical limits while maintaining continuous work precision and quality.
- Cognitive System: Humans are generally capable of high levels of cognitive ability when given enough time. However, this skill is frequently constrained by tight boundary conditions (*e.g.*, time constraints) and hindered by the lack of a holistic context view. To improve this skill, the operator can benefit from the assistance of a different cognitive system, such as an intelligent multi-agent system, which will provide advice on making the best global decision possible.
- Mixed Reality: Humans rely on direct senses to comprehend their surroundings but with fading memories of the past and decreasingly reliable future predictions. A mixed reality technology or a digital twin can help alleviate this incapacity. As a result, people will be able to see what is currently invisible as well as what may happen in the future, making it possible to avoid making bad decisions.
- Co-Intelligence: Collaborative intelligence is built on the primitives of humans-assisting-robots (train, explain, maintain) and robots-assisting-humans (amplify, interact, embody). People must use their competencies to teach robots how to perform and explain how decisions are made to sustain. Robots must assist humans in self-adapting to interact with labour to their full (artificial and anthropological) potential.

IV. Industry 5.0 Technologies

Industry 5.0 technologies are crucial to the advancement and success of modern manufacturing. Advanced sensors and data analytics can assist manufacturers with real-time monitoring of manufacturing processes, allowing them to detect and correct quality issues. It helps to reduce waste and flaws and improve the overall quality of products. As illustrated in Fig. 5, various Industry 5.0 enabling technologies such as DT, IoE, 6G, cobots, blockchain, and big data analytics are consolidated with thought processes and creativity. These trends help industries to deliver customized products and increase productivity more rapidly. Industry 5.0 is a concept of energy sharing and peer-to-peer energy exchanges [5]. In this paradigm, industries use edge computing technology to build decentralised energy networks that exchange excess energy securely and transparently with other organisations. By engaging in energy-sharing networks, industries optimise

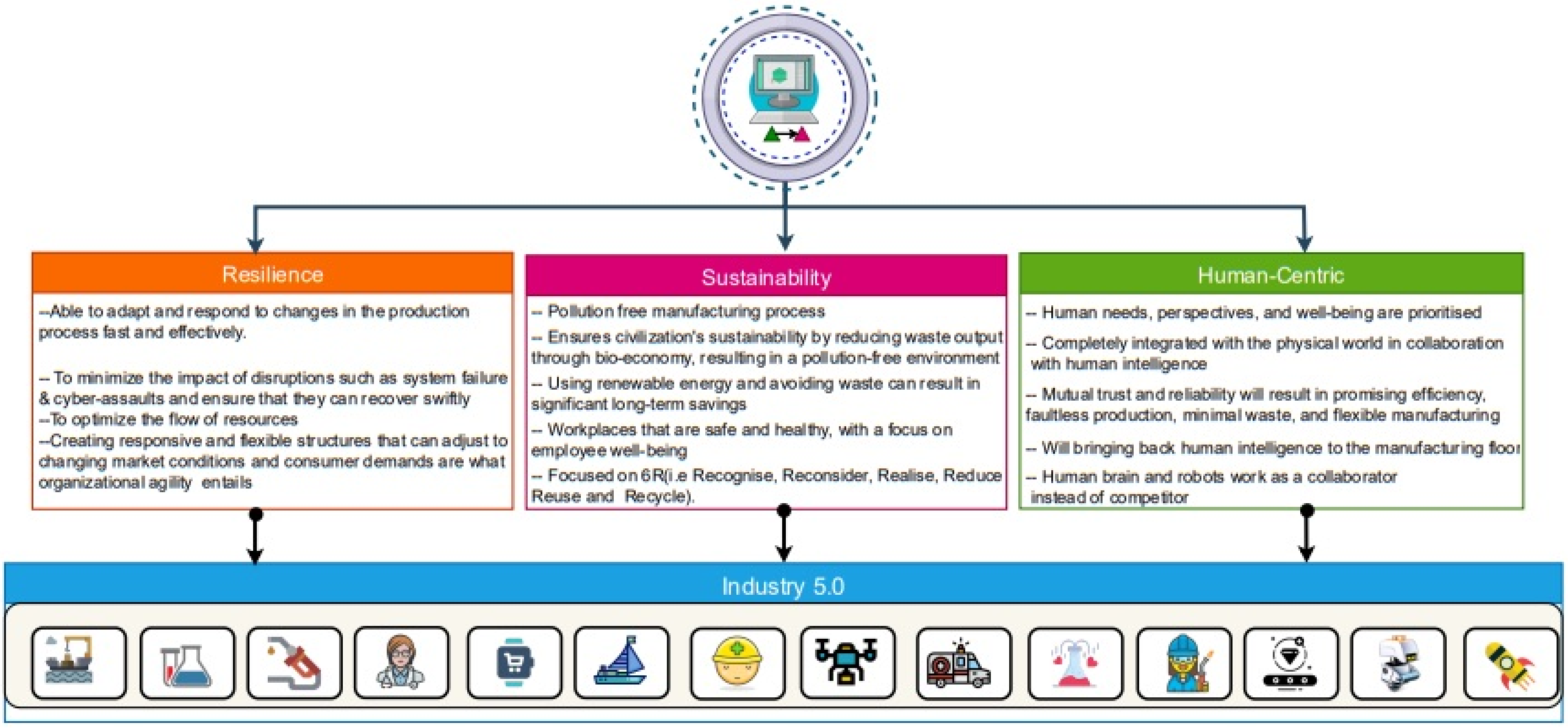

Fig. 4. Industry 5.0 objectives and their functionalities.

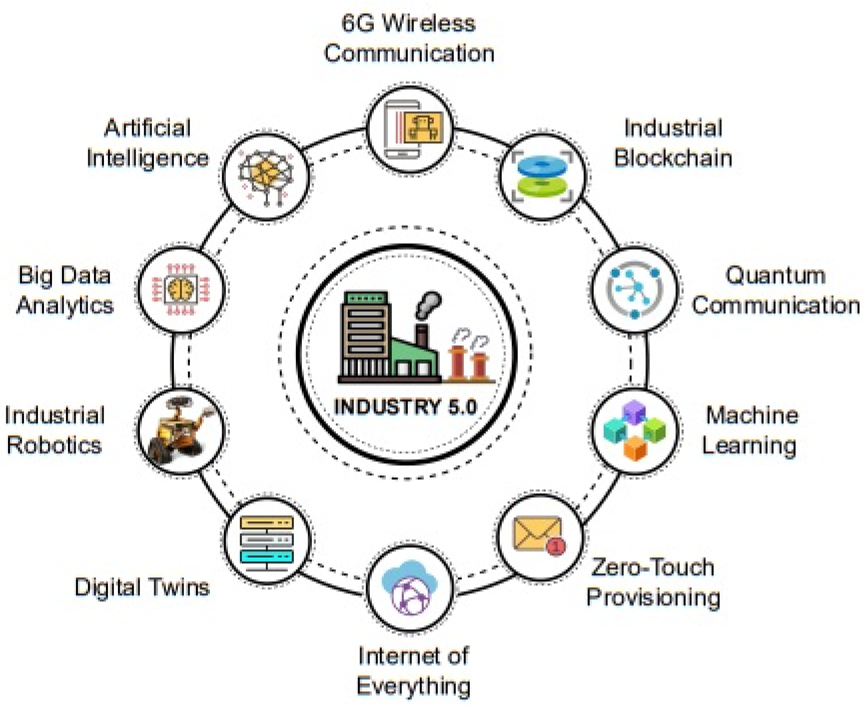

Fig. 5. Cutting-edge technologies powering Industry 5.0.

energy usage, cut energy costs, and create a more sustainable and resilient energy ecosystem. It enables industries to interact and trade energy resources, resulting in efficient utilisation and waste reduction. Industry 5.0 revolutionises how energy is consumed, managed, and allocated by adopting energy sharing and peer-to-peer transactions, ultimately promoting economic growth while lowering total energy costs and environmental impact.

A. 6G Wireless Communications

Wireless communication is becoming increasingly vital as we shift towards a more human-centred approach to manufacturing. This is where 6G wireless connection comes in, with faster speeds, lower latency, and more reliability than previous generations. 6G can provide Industry 5.0 with multiple value-added services. For instance, it can offer better security features such as network slicing, increasing network security and customisation while lowering cyberassault risk. This is especially significant in Industry 5.0, where combining new technologies with traditional industrial processes might increase the danger of cyber assaults [20]. Its ability to transmit data at extremely high speeds. According to current research, 6G networks could provide data transfer rates up to 1 Terabyte per second (TB/s), significantly faster than the current maximum speed of 5G networks, around 20 Gigabytes per second (GB/s). This increase in data transfer rates will enable new applications, such as real-time high-definition video streaming, VR experiences, and cloud gaming.

6G wireless communication is predicted to be more reliable. This dependability is achieved through advanced technologies such as massive MIMO (Multiple-Input Multiple-Output), which allows multiple antennas to send and receive data simultaneously, and beamforming, which allows specific devices or areas to be targeted with a focused signal. These technologies will allow 6G networks to provide improved coverage, especially in locations with high user density or environmental interference. Incorporating edge computing with 6G wireless communication has the potential to enable new applications and use cases in Industry 5.0. For example, in smart cities, edge computing could enable real-time monitoring and analysis of traffic patterns, air quality, and energy consumption, leading to more efficient use of resources and improved quality of life for citizens.

B. Industrial Blockchain

Industrial blockchain is significant in Industry 5.0, particularly with edge computing. In Industry 5.0, centralised control of many heterogeneous linked devices is a crucial challenge. By enabling distributed trust, blockchain can construct decentralised and distributed management platforms [21]. It has been shown that peer-to-peer communication using blockchain technology provides a permanent record-keeping system. Additionally, the immutable ledger promotes operational accountability and transparency for critical events in Industry 5.0 applications. Industrial blockchain technology creates a safe and transparent platform for collaboration and communication among producers, suppliers, and customers. This leads to better relationships and decision-making. Smart contracts will be used in future Industry 5.0 apps to ensure security through authentication and automated service-oriented processes. On the one hand, industries will benefit from securing their data and privacy by incorporating edge networks. On the other hand, this cooperation enhances the distributed computing functionalities of the industrial environment, making the industrial environment resilient. Moreover, network access may be limited or unreliable in certain industrial situations. Therefore, incorporating edge computing allows edge devices to operate offline while synchronising data with the central blockchain network when the connection is restored. This guarantees continuous operation and data integrity.

C. Quantum Communication

Quantum communication networks are groups of nodes linked via quantum communication channels. These networks are built with specialised hardware, such as single photon sources, detectors, and quantum memory. The network's nodes are placed in data centres or at the network's edge. Quantum communication networks must integrate edge computing with sensors and mobile devices. This involves developing interfaces and protocols that enable edge devices to communicate securely with quantum communication networks. Quantum Key Distribution (QKD) help to establish a shared key between two nodes in a secure manner. QKD is a revolutionary key distribution algorithm that uses quantum physics laws to distribute random secret keys between two users even when an eavesdropper is present. QKD is built around the principles of the no-cloning theorem and Heisenberg's uncertainty principle [22]. QKD involves sending single photons via a quantum channel. Any effort to measure or intercept these photons disturbs their quantum state, allowing the transmitter and receiver to detect the existence of an eavesdropper. Messages are encrypted and decrypted using a shared key. Edge computing applications that take advantage of quantum communication's secure and efficient data transport can be built. For instance, ML algorithms run on edge devices using data safely sent across the quantum communication network.

D. Machine Learning

Industry 5.0's primary accelerators include ML. Real-time data collecting and computation tasks are split between edge servers and devices for effective online ML training. Sending entire device datasets back to the cloud servers is too expensive and poses privacy issues. Integrating online ML training directly with edge or wireless devices, such as mobile phones, sensor networks, smart transportation, IIoT, etc., has received much attention in recent years. Edge learning framework, fog learning, and federated learning on vehicular nodes are just a few of the ML methods specifically developed for edge computing architectures by academia and industry [23]. Moreover, adopting and integrating ML algorithms is another emerging trend in industrial applications. These applications use ML algorithms for various purposes, for instance, decision-making in ambient intelligence and smart environments, pattern recognition in objects and scene understanding in augmented reality, face recognition for real-time identity verification, behaviour prediction in mobile gaming and autonomous vehicles, and viewport prediction for video streaming.

E. Zero Touch Provisioning Standard

As the number of IoT devices grows, the difficulties of quickly installing them, configuring them for the first time, and getting them to work have become more imperative. In next-generation IoT networks, manually setting up many different types of devices can slow things down and lead to mistakes and breakdowns. ZTP created a solution to these problems. It allows a wide range of devices to be set up automatically and without human intervention. The Zero-Touch Network and Service Provisioning (ZNSP) standard, published by ETSI in 2019, aims to automate all manufacturing processes. It is still challenging to achieve zero-touch technology, even in Industry 5.0. The self-serving, self-fulfilling, and self-assuring nature of zero-touch services makes it a promising standard.

It's important to realise that achieving full automation, especially using self-learning features, brings new problems like collaborative intelligence, 5G network slicing, data protection, insufficient workforce training, customization, and more. Furthermore, ZNSP wants to fully automate production, while Industry 5.0 wants to include humans in the production process, making it difficult to understand the future of production. Key attributes of a ZTP approach include user-friendly usability, enabling provisioning by individuals without technical knowledge; interoperability, ensuring compatibility across different vendors and systems; robust security measures to safeguard the integrity of credentials during the provisioning process; ease of implementation, requiring minimal additional equipment or complex infrastructure; and scalability, allowing the network to seamlessly adapt to changes such as the inclusion of new devices or the expansion of capacity [24].

F. Internet of Everything

IoE is a network that connects people, processes, information, and things [25]. It brings various functions like a better user experience and anticipated advantages for sectors and countries. It increases customer satisfaction and loyalty and creates customised experiences using data supplied by IoE [26]. It enables the real-time collection of enormous amounts of data from various sources, such as consumer feedback, social media, and device usage trends. ML algorithms help to analyse this data and uncover patterns and trends to improve consumer experiences. For example, an IoE-enabled intelligent home system can analyse user behaviour and preferences to recommend personalised products and services. By removing congestion from communication lines and lowering latency, Industry 5.0's use of IoE offers the chance to cut operating costs. As time has passed, humans have shared information wirelessly, primarily with wireless sensors. For instance, the medical field connects sensors to the patient. These sensors identify patient irregularities and send information to the doctor or nurse. Based on the findings, doctors will take proper action. Indeed, incorporating edge computing into IoE involves deploying edge devices, such as gateways or edge servers, to process data locally. These edge devices are outfitted with sensors and processing power, such as Graphics Processing Units (GPUs), for real-time data processing and analysis.

G. Digital Twin

A DT is a digital replication of a physical system or object. It helps to represent wind farms, industries, jet engines, buildings, and even larger systems such as smart cities digitally. [27]. Although the notion of DT was proposed in 2002, it has only recently become a reality because of the growth of IoT. IoT reduced the cost of DT, making it more accessible and economical to a wide range of sectors. Data from physical things are transmitted to their digital counterparts for simulation via IoT devices. This digital mapping of real-time objects/systems via DT allows for monitoring, analysis, and prevention of issues before they occur in the real world. Due to the rapidly growing use of cutting-edge technologies, DT has decreased maintenance costs and increased system performance. This is done using software that simulates the behaviour of the equipment or system. The model should capture all the parameters and variables affecting the equipment or system's performance. Afterwards, connect DT to an edge computing system to process the data in real-time. This is done using various connectivity options like Wi-Fi, Ethernet, or Bluetooth. The data is collected from a physical object or system via sensors. As the data from the physical equipment or systems are collected, they are sent to the edge computing system for analysis with the help of ML algorithms.

H. Industrial Robotics

Industrial robotics refers to using advanced robotic systems in manufacturing and industrial processes. In just a few decades, robots completely transformed the industrial environment. The concept of designing and building creatures or equipment that might perform repetitive or heavy duties, thus freeing men of this burden, reaches back to ancient times. They are normally made up of a controller, a power supply, a manipulator, and an end-effector. They are programmed with sophisticated software that allows them to do a wide range of tasks with high precision and accuracy [28]. They are outfitted with a range of sensors, such as cameras, lasers, and proximity sensors, which allow them to detect and respond to changes in their surroundings. They can also be programmed with complex algorithms for collision avoidance, path planning, and other critical functions. With the tremendous and rapid advances in AI technology, it is evident that all gadgets with computational capabilities have become more intelligent. Collaboration between humans and robots helps make human capabilities more efficient and straightforward [29].

I. Big Data Analytics

The industrial environment has undergone a phenomenal change due to the rapid development of information and communication technology. The introduction of cutting-edge technology leads to changes in the manufacturing processes that transform manual production methods into machine-driven ones. This manufacturing process automation brought on the Industrial Revolution. The massive amount of data (big data) has been generated as a result of the development of the social web, and its effective use has helped to shape the fifth industrial revolution [30]. Big data analytics is essential in developing an intelligent and sustainable industry. Big data analytics makes real-time analysis possible through sophisticated algorithms, delivering actionable insights to enhance product quality, reduce downtime, and optimise manufacturing processes. It also helps with predictive maintenance, enabling proactive servicing of equipment prior to breakdowns.

V. Applications of Industry 5.0

The application of Industry 5.0 offers several benefits, such as emphasising collaboration between humans and advanced technologies. The goal is to establish a harmonious working atmosphere that merges human skills, creativity, and problem-solving abilities with automation accuracy and efficiency. Furthermore, it improves manufacturing safety, decreases accidents and injuries, and makes production operations more efficient and productive. It helps to reduce costs by optimizing manufacturing processes and increasing productivity. Moreover, Industry 5.0 applications contribute to sustainable practices by eliminating waste and optimising resources. IoT and data analytics integration allow real-time monitoring and control of energy consumption, material utilisation, and manufacturing processes. This results in better resource allocation, less environmental impact, and economic savings. Various potential applications of Industry 5.0 are shown in Fig 6, their challenges and how Industry 5.0 can help to solve these challenges are shown in Table III.

A. Predictive Maintenance

Predictive maintenance is one of the emerging application areas in Industry 5.0, also known as online monitoring, condition-based maintenance, or risk-based maintenance. When equipment starts to fail, it may show signals that can be identified if sharp eyes, ears, and noses are utilised to detect the failure precursors. Fortunately, sensors are now available to detect degradations and malfunctions of devices before they cause damage. This helps to save money by avoiding unnecessary equipment replacement and improving process safety, availability, and efficiency. This technique works in that the targeted asset is the source of the imported data, which is subsequently synthesised and aggregated with many other data sources. Once a substantial amount of data has been thoroughly cleansed, data analysis is undertaken to discern prevailing trends and patterns. Ultimately, the system can produce predictive models to anticipate forthcoming occurrences by employing ML and AI methodologies. A manufacturing industry that depends on a fleet of industrial machinery for production. A crucial machine in the industry is outfitted with sensors to oversee many characteristics, including temperature, vibration, and pressure. Sensor data would be consistently transmitted to a centralised cloud server for analysis in a conventional configuration without edge computing. The data would be processed by predictive maintenance algorithms operating on the cloud, utilising historical trends to forecast the timing of repair needs. Afterwards, the outcomes and notifications would be transmitted back to the industries. The machine has been upgraded with edge computing, which integrates edge devices that can process data locally. ML models are implemented on these edge devices to analyse the real-time sensor data. The edge devices do local data processing instead of sending all raw data to the cloud, transmitting pertinent insights or alarms.

B. Collaborative Supply Chain

Globalised and highly competitive business environments have led manufacturers to realise they must provide the highest customer value at the lowest possible cost to maintain a competitive advantage. Customers increasingly seek faster reaction times, shorter product cycles, and customised products and services. Central servers frequently experience information overload, leading to expensive processing delays. Therefore, edge computing enhances supply chain efficiency by optimising resource allocation, reducing dependence on human oversight, and significantly improving the response time for time-critical operations. With the increasing investment in IoT devices and the growing need for faster outcomes in warehousing and transportation operations, edge computing emerges as a profitable choice for companies seeking logistics management solutions. Additionally, collaboration between supply chain partners allows organisations to pursue business goals. As a result, cooperative behaviour and activities in supply chain management have grown in relevance [31]. Industry 5.0 collaborative supply chains prioritise system, process, and data format standardisation and interoperability. This allows smooth integration and communication among various entities in the supply chain, promoting effective collaboration. Organisations may optimise resource utilisation, eliminate waste, and design more sustainable goods and processes by working closely with suppliers and customers. Furthermore, incorporating edge computing helps in such a way that collaborative supply chains frequently operate in various settings, including rural or isolated places. When connectivity is restricted or sporadic, edge computing allows offline capability by enabling edge devices to process and store data locally. Even under difficult network conditions, this ensures uninterrupted operations and data integrity.

C. Intelligent Healthcare

Intelligent healthcare plays a crucial role in Industry 5.0, merging digital and conventional industries to drive innovation, efficiency, and sustainability. It allows for remote consultations, telemedicine, and remote patient monitoring, bridging geographical and socioeconomic inequalities in healthcare

Fig. 6. Emerging Industry 5.0 applications.

access. This is particularly critical in Industry 5.0, where connectivity and digital infrastructure allow equitable healthcare access regardless of geography or socioeconomic position. Doctors use ML models to diagnose illnesses, saving time and money [32]. Nevertheless, it is not enough in the present day to address personalized patient needs, like monitoring blood pressure and sugar levels and providing tailored treatment with doctors' assistance. For instance, healthcare presents numerous cutting-edge prospects. Currently, monitoring devices such as glucose monitors, health tools, and other sensors are either not linked together, or if they are, significant quantities of unprocessed data from these devices would have to be kept on an external cloud service. This poses security risks for healthcare practitioners. The medical facility might utilise edge computing to process data locally, ensuring data privacy preservation. Edge also facilitates real-time notifications to healthcare professionals regarding atypical patient patterns or behaviours (using analytics and artificial intelligence) and the development of comprehensive patient dashboards for complete visibility.

Smart wearables such as smartwatches and wearable sensors can continuously capture and analyze patient data through ML methods. These smart gadgets may communicate with one another, allowing doctors to observe the patient's current state and alert them if intervention is required. Surgeons are using robots that communicate with one another to assist them in operating on patients with the help of cobots [5]. In telemedicine and distant care settings, edge computing is critical. Healthcare providers distantly diagnose and treat patients by delivering computational capability to the edge rather than depending primarily on centralised servers. Edge technologies can process high-resolution medical imaging, facilitate real-time video consultations, and support remote monitoring, allowing patients to obtain prompt care from their homes. This functionality is especially useful for people living in distant places or having limited healthcare access. Moreover, industrial healthcare keeps workers safe by detecting and controlling occupational hazards. This includes risk assessments, implementing safety protocols, providing Personal Protection Equipment (PPE), and training staff on safe practices.

D. Production System

The production system in Industry 5.0 turns traditional manufacturing into an intelligent, collaborative, and sustainable ecosystem. Intelligent manufacturing relies heavily on production systems. Industrial resources are created and developed with virtual (digital) resources associated with physical resources throughout their existence. With the recent rise of ICTs such as big data, VR, and the IoT, the interconnection and interaction of physical and virtual resources in production systems have become conceivable. Furthermore, edge computing improves the reliability and resilience of production systems. Local processing and storage capabilities at edge devices ensure that critical production operations can continue even if the network is disrupted or there is a latency issue. Edge devices are self-contained and make decisions based on local data, maintaining continuous production and minimising downtime [33]. For instance, in an Industry 5.0 setting, edge devices could analyze product surfaces for imperfections or ensure precise assembly. Any deviations from quality standards trigger immediate corrective actions, reducing waste and improving overall product quality.

E. Society 5.0

Society 5.0 is the creation of an open society guided by technological and scientific innovation, whose focus is to create a human-centred, super-smart and lean society, which was initiated by the Japanese government in the year January 2016 [34]. Society 5.0 was implemented in Japan to balance economic growth and address social issues (such as the ageing population, low birth rates, and lack of competitiveness). In Society 5.0, edge computing enables decentralised systems and peer-to-peer networks. Edge computing allows distributed applications and services by allowing edge devices to communicate and share resources without relying on centralised servers. Due to this decentralisation, individuals and communities benefit from increased autonomy, resilience, and collaborative decision-making. Society 5.0 aims to ensure that all its citizens have access to high-quality lives that are comfortable and full of vitality by providing the essential goods and services for specific individuals at the necessary level when needed by fusing cyberspace and physical space with advanced technologies. In actuality, human society has gone through four changes, namely hunter-gatherer society (Society 1.0), agricultural society (Society 2.0), industrial society (Society 3.0), and information society (Society 4.0), and is currently entering a smart civilization valuing humans (Society 5.0). Human centricity is the essential element in both Society 5.0 and Industry 5.0. Individualized service systems, intelligent manufacturing systems, and other systems will all contribute to the value of Society 5.0.

F. Metaverse

Metaverse is the futuristic type of Internet application and social form that consolidates a variety of new technology [35]. The metaverse is a computer-generated environment with a consistent value system and an independent economic system connected to the real world. The name comes from the combination of the word *meta* (which means transcendence) with the suffix *verse*, which is short for the *universe*. It generates a mirror picture of the natural world using DT technology. It enables users to create content and edit the world by integrating the real and virtual worlds into social, economic, and identification systems. In the future, the metaverse will have a lot of potential for use in virtual manufacturing and simulation. For instance, manufacturers use the metaverse to create virtual replicas of their production lines, equipment, and procedures, making it easier to simulate and prove their processes. This enables virtual testing, optimisation, and simulation of manufacturing activities, eliminating the need for actual prototypes and expensive trial-and-error methods. Manufacturers can enhance and optimise their processes in the metaverse before adopting them in the physical world [36]. As a result, many researchers and practitioners have begun to deploy the metaverse in industrial services. For example, a Japanese airline started offering virtual flights from Tokyo to numerous locations (*e.g.*, Rome, Paris, and New York). Moreover, edge computing enables deploying edge AI models to power intelligent virtual agents in the metaverse. Edge devices may process user inputs in real-time, analyse the context, and provide dynamic answers, resulting in more engaging and personalised experiences. Edge AI also enables virtual agents to adapt and learn from human behaviours, increasing the realism and intelligence of metaverse avatars.

G. Industrial Transportation

Transport plays a very important role within Industry 5.0, which focuses on integrating sophisticated technology and collaborative production practices to integrate manufacturing and production processes into one seamless process. The traditional transportation industry is being transformed by Industry 5.0, which uses cutting-edge technologies to improve efficiency, sustainability, and responsiveness through advanced technologies. Transporting commodities from distribution centres to end users is one of the most important aspects of the industrial transportation industry. Technology such as drone deliveries, self-driving cars, and crowd-shipping platforms are aiding last-mile delivery efficiency, cutting delivery times, and increasing customer satisfaction. Furthermore, autonomous transportation, which refers to cars that can operate without human intervention, is gaining popularity and is expected to impact the industry significantly. For instance, autonomous platooning of truck convoys is expected to be among the

TABLE III
APPLICATIONS, CHALLENGES, AND THE ROLE OF INDUSTRY 5.0.

Applications	Challenges	How Industry 5.0 can help
Predictive Maintenance	The availability of high-quality data is critical for predictive maintenance. Obtaining meaningful and trustworthy data from numerous sensors, equipment, and systems is difficult, especially in older or less-connected infrastructure.	Industry 5.0 allows the smooth integration of data from many sources by introducing standardised protocols and data exchange frameworks. This facilitates access to essential data for predictive maintenance analysis and reduces data availability and integration problems. Connect devices, sensors, and systems securely using industry-standard protocols. By deploying an edge computing infrastructure, ensure connectivity between edge devices and the central data infrastructure.
Collaborative Supply Chain	Building confidence and developing cooperation among supply chain partners are quite challenging, especially when several organisations are engaged with diverse aims, cultures, and priorities.	Industry 5.0 emphasizes the need for trust and security in collaborative supply chains. Edge computing improves the collaborative supply chain's security and privacy. Edge devices use encryption, access controls, and security protocols to protect data and prevent unauthorised access. Improved security and privacy safeguards foster trust among partners while assisting in compliance with data protection standards.
Intelligent Healthcare	Interoperability is the ability of several systems and devices to communicate information and work in unison. A major challenge for the healthcare industry is the lack of interoperability between healthcare systems.	Edge data processing decreases delays and promotes real-time interoperability. With the help of smartwatches and smart sensors, healthcare data can be continuously recorded in real-time and stored in the cloud. Patients' medical conditions can be diagnosed using ML algorithms. Smart gadgets can communicate with each other, and if a doctor's attention is needed, these devices can let the doctor know the patient's current condition.
Production System	Fluctuations in customer demand present obstacles to production systems. Rapid fluctuations in demand volume or mix can lead to underutilization or overutilization of manufacturing capacity, resulting in inefficiencies and cost increases.	Design flexible or modular manufacturing systems that easily accommodate product variants and variable production volumes. Edge computing enables distributed processing and scalability in commercial systems. Additional edge devices can be deployed as needed to meet rising production demands. This gives flexibility and agility in increasing manufacturing operations without relying only on centralised systems. Monitor inventory levels, lead times, and reorder points using advanced management tools and procedures.
Society 5.0	With Industry 5.0, the benefits of Society 5.0 may be dispersed relatively across society. Adopting modern technology may result in more automation and job displacement, disproportionately impacting low-skilled employees.	Industry 5.0 helps to resolve concerns about unequal benefit distribution. Edge computing brings computing resources closer to end-users and devices, lowering latency and improving connectivity. Edge devices offer smooth and uninterrupted interaction between humans, devices, and systems by processing data locally. By supporting sustainable development, innovation, cooperation, digital inclusion, and a human-centred approach, Industry 5.0 can help tackle numerous problems in Society 5.0.
Metaverse	The metaverse requires a robust, high-speed network architecture for real-time data transfer. Universal access to such infrastructure worldwide is challenging, particularly in impoverished or isolated areas.	Including high-speed internet access, 5G networks, and edge computing will help to face the challenges. The time it takes for interactions and actions to be processed and reflected in the virtual environment is reduced by processing data locally on edge devices or servers. This enhances the user experience by making metaverse interactions more responsive and immersive.
Industrial Transportation	Industrial transportation contributes to carbon emissions and environmental contamination. Managing transportation operations sustainably is becoming increasingly challenging.	Industry 5.0 encourages modern technologies such as electric vehicles, hybrid systems, and alternative fuels to enhance fuel efficiency and minimise carbon emissions. Edge devices eliminate the need for huge volumes of data to be transmitted to centralised systems or the cloud by processing data locally at the edge, which consumes significant network bandwidth and energy.

initial applications of autonomous vehicles. Here, a truck fleet closely follows each other in a convoy, reducing fuel expenses and alleviating traffic congestion. Edge computing eliminates drivers in all trucks except the front one by facilitating seamless communication between the trucks with minimal delay. Moreover, the transportation sectors could lessen their carbon footprint by optimising routes, reducing traffic, and reducing parking demand. Electric automobiles driving themselves may also become more prevalent, reducing pollution [37].

VI. CHALLENGES

Industry 5.0 completely transforms production, benefiting businesses, workers, and consumers. This section will examine some potential challenges and research directions for Industry 5.0. As modern technology becomes more integrated into industrial processes, the workforce must learn various skills and adapt to changing employment needs. To ensure a smooth transition, this shift may result in job displacement and the need for retraining and upskilling programmes. Therefore, the workforce's adaptability to new technologies and working techniques is one of the most severe problems of Industry 5.0.

Future research directions for developing human-robot cooperation technologies are one of the primary research objectives for Industry 5.0. These technologies will allow robots to operate alongside people in a safe environment, increasing production and efficiency while ensuring safety and reducing the chance of accidents. Industry 5.0 intends to build smart factories that are ultimately linked, automated, and flexible. Smart factories will require advanced IoT technology such as sensors, connectivity, and data analytics to enable real-time monitoring and optimisation of production processes. AI and ML will be meaningful in Industry 5.0, allowing robots to learn from data and improve their performance over time. Developing advanced algorithms and ML models that learn from massive datasets will be critical to realising Industry 5.0's full potential.

A. Heterogeneity and Data Security

Heterogeneity pertains to the presence of diverse platforms, architectures, infrastructures, computing, and communication technologies utilised by the elements of edge computing (such as end devices, edge servers, and networks). The main factors contributing to end-device heterogeneity are software, hardware, and technology variations. The primary cause of heterogeneity on the edge server side is the presence of APIs, custom-designed policies, and platforms. These differences lead to interoperability problems, making it a primary challenge to implement edge computing in Industry 5.0 effectively. During deployments, Industry 5.0 will experience serious security problems. Industry 5.0 must fulfil security requirements, including integrity, availability, authentication, and audit elements, just like conventional CPSs do. Building confidence in the ecosystem is essential to authenticating many stakeholders, including machines, IoT nodes, fog nodes, collaborative partner nodes, and communication nodes [38].

Industries rely so heavily on wireless communication that they are susceptible to jamming attacks. Additionally, the interconnectedness of IoT devices amplifies the potential damage, necessitating the implementation of strong security measures by industries to mitigate this susceptibility [39].Industry 5.0 authentication solutions should be lightweight to deploy with IoT nodes, scalable to connect billions of devices, and quantum-resistant to fend off future quantum computing applications. Utilising AI and automation in Industry 5.0 will introduce a novel vulnerability. Trusted execution is crucial for ensuring security in AI/ML operations. It is essential to safeguard the integrity of the dataset utilised for training ML models and AI algorithms to ensure their effective functioning in Industry 5.0. For example, in Industry 5.0, various tenants should securely exchange empirical data to train AI models or make incremental updates to the models, similar to the concept of federated learning. Furthermore, the notable applications of Industry 5.0 heavily rely on ICT systems, resulting in new security needs, including implementing proactive security measures and preventing Zero-day attacks. Furthermore, the advancement of quantum computing could enable Industry 5.0 to function in the era of quantum computing. A quantum computer will greatly simplify the safeguarding of traditional security methods. In such circumstances, Industry 5.0 systems ought to employ quantum-resistant encryption or post-quantum cryptography mechanisms to ensure the necessary level of security.

B. Privacy and Trust

Privacy is essential for Industry 5.0 applications since the entire ecosystem relies on pricey intellectual property, expensive manufacturing components, and subscription management. Data is transmitted through the Internet in Industry 5.0 to connect machines and people, designers and other partners, and to convey monitoring and control information [40]. Transparency, responsibility, and moral behaviour are the cornerstones of Industry 5.0 trust. Industries must be open and honest about gathering and utilising data, giving brief and comprehensible justifications for each step in the process. Integrate differential privacy techniques into edge computing systems to secure the privacy of individual data. It introduces noise or disturbances into data to ensure privacy while allowing correct aggregate analysis. Personal information can be secured while allowing for relevant analysis and insights by implementing differential privacy at the edge.

Blockchain is a decentralised technology that utilises a distributed ledger to store information in a transparent, unchangeable, and highly secure manner. Additionally, it is more resource-intensive as it requires more energy to extract the data from its nodes. However, it guarantees data security by employing digital hashes of the preceding records. Blockchain technology has the potential to make a substantial impact on privacy concerns in Industry 5.0. Due to the resource-intensive nature of the blockchain, a rise in the number of nodes in Industry 5.0 applications based on blockchain technology may result in a slowdown. To mitigate this issue, one can implement a lightweight blockchain structure by separating infrequently utilised data from the main blockchain and placing it in a separate sidechain. Moreover, quantum computing can enhance the security of the CPS or CPPS without experiencing any periods of system unavailability. To ensure the necessary level of security, it is advisable to employ either quantum-resistant cryptography or post-quantum cryptography mechanisms.

C. Human-Robot Co-working Infactory

Humans will again work alongside cobots on the production floor with the evolution of Industry 5.0. Although it appears to be a productive technique for creating customised products, specific concerns about the interaction between humans and robots must be considered. Additionally, job loss anxiety will be reduced when humans and robots share labour. The cobot will do the routine tasks, freeing the human to focus entirely on innovation and creativity. It will be preferable for cobots to support humans than the other way around, which might lead to organisational instability and complicate the company's long-standing job competitiveness culture. Additionally, cobot workers are skilled and may have higher expectations than a traditional workplace culture [41]. Use edge computing to optimise resource allocation in the production between people and robots. Edge devices can monitor human and robot workloads, availability, and capabilities, allowing for dynamic task allocation based on efficiency, skill sets, and real-time situations. This guarantees that tasks are assigned to the best entity for the job, increasing efficiency and reducing bottlenecks.

D. Sustainable Environment

Industry 5.0 has the potential to advance productivity beyond the profit-centred productivity of Industry 4.0 and to advance sustainable development objectives, including human-centricity, socio-environmental sustainability, and resilience [42]. By integrating environmentally friendly practices into the design, development, and use of industrial processes and systems, sustainability in Industry 5.0 can be realised. Using clean and renewable energy sources like solar, wind, and hydropower can be encouraged through Industry 5.0. Using renewable energy systems in industrial operations can lessen carbon emissions and contribute to developing a sustainable energy future. Adopting circular economy concepts, which aim to reduce waste and promote resource reuse, can enhance resource efficiency. Industrial processes can be less environmentally impactful using sustainable materials. They can facilitate the use of sustainable materials like bioplastics and recycled materials, which can help minimise waste and preserve natural resources. Use edge computing to monitor factory emissions in real-time. Edge devices collect emission sensor data, analyse emission trends, and provide alerts or feedback on emission levels. By monitoring emissions at the edge proactively, factories may identify areas for improvement, implement emission reduction initiatives, and comply with environmental standards.

E. Resilient Network

The ability of the industrial network to withstand and recover from disturbances brought on by internal or external forces is referred to as resilience in Industry 5.0. Industry 5.0 calls for adopting technology and practices that guarantee business continuity and reduce downtime. Some strategies can promote stability by implementing redundancy and backup systems that guarantee ongoing operation in the case of disruptions. By implementing strong cybersecurity measures that guard against online dangers like hacking, malware, and ransomware assaults. Advanced encryption techniques, secure networks, and firewalls can all be used to accomplish this by embracing interoperable technologies and systems that can easily interface with other systems [15]. In the event of disruptions, this can reduce downtime and ensure company continuity by providing predictive maintenance solutions that employ data analytics and AI to find and fix equipment issues before they happen. This helps to reduce downtime and ensure uninterrupted operation.

F. Skilled-Workforce

Standardisation and legal standards must be enforced to tackle technology, societal, and management challenges because a skilled worker in Industry 5.0 must offer a high-value production task. Providing a qualified workforce involves several considerations for management, employees, company culture, management infrastructure, and general policies. Various industries would readily embrace the emerging technology, while management may need more comprehension of its implications. The proficient staff and the prevailing culture have the potential to take advantage of the management's lack of knowledge. In addition, if the employees lack forward-thinking abilities, it will result in significant training expenses from a managerial standpoint. The senior employee may require more time to adjust, and reengineering efforts may also be necessary. Furthermore, several organisations may need more infrastructure to support the implementation of the new technology. Therefore, it is essential to consider these factors while establishing a transparent corporate culture and ensuring the long-term acquisition of talented staff. Consequently, this will expedite future business changes. Consistent and efficient training for humans and cobots will prevent most collaborative work problems. In addition, providing ongoing training for operational workers will guarantee a highly skilled workforce. To ensure the necessary level of security, it is advisable to employ either quantum-resistant cryptography or post-quantum cryptography mechanisms.

G. Industrial Standardization

The creation and implementation of uniform standards for the planning, creating, and managing industrial systems and procedures are referred to as standardisation in Industry 5.0. Interoperability, cost savings, and increased productivity can all be achieved by standardisation in industrial operations. The General Data Protection Regulation (GDPR) and the California Consumer Privacy Act (CCPA) are important industry data protection legislation. Global GDPR enforces strict data processing regulations, and California's CCPA protects consumers' privacy rights and affects industries that operate in the state. Moreover, the International Society of Automation (ISA) is the leading organisation for establishing standards and rules and providing industry experts with training and education in automation to improve operational excellence. The objectives of ISA are to increase safety, simplify component integration, and offer unwavering instrumentation. The American National Standards Institute (ANSI) is a non-commercial organisation that manages global agreement standards development, collaborating with ISA to produce standards for industrial control systems [43]. ANSI and ISA have developed various industrial control system standards. It includes practices for the alarm system in industrial processes (ISA18), safety and practical application of hazardous environment equipment (ISA12) [44]. Moreover, Germany has a long history of maintaining strong manufacturing standards for emphasising quality, efficiency, and innovation across various businesses. Germany takes an active role in creating and using International Organisation for Standardisation (ISO) standards. German industry frequently uses ISO 9001 (Quality Management Systems) and ISO 14001 (Environmental Management Systems) to ensure quality control and sustainability [1].

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