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Industry 5.0: A survey on enabling technologies and potential applications ☆

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ABSTRACT

Industry 5.0 is regarded as the next industrial evolution, its objective is to leverage the creativity of human experts in collaboration with efficient, intelligent and accurate machines, in order to obtain resource-efficient and user-preferred manufacturing solutions compared to Industry 4.0. Numerous promising technologies and applications are expected to assist Industry 5.0 in order to increase production and deliver customized products in a spontaneous manner. To provide a very first discussion of Industry 5.0, in this paper, we aim to provide a survey-based tutorial on potential applications and supporting technologies of Industry 5.0. We first introduce several new concepts and definitions of Industry 5.0 from the perspective of different industry practitioners and researchers. We then elaborately discuss the potential applications of Industry 5.0, such as intelligent healthcare, cloud manufacturing, supply chain management and manufacturing production. Subsequently, we discuss about some supporting technologies for Industry 5.0, such as edge computing, digital twins, collaborative robots, Internet of every things, blockchain, and 6G and beyond networks. Finally, we highlight several research challenges and open issues that should be further developed to realize Industry 5.0.

1. Introduction

Vehicles, clothing, houses and weapons have been designed and manufactured by humans and/or with the help of animals in the past centuries. With the emergence of Industry 1.0 in 1974, industrial production began to change significantly. Fig. 1 shows an overview of the evolution of Industrial $X.0$ [1]. The development time for the first three revolutions was around 100 years, and it took only 40 years to reach the fourth from the third. In 1800s, Industry 1.0 evolved through the development of mechanical production infrastructures for water and steam-powered machines. There is a massive gain in the economy as production capacity has increased. Industry 2.0 evolved in the year of 1870 with the concept of electric power and assembly line production. Industry 2.0 focused primarily on mass production and distribution of workloads, which increased the productivity of manufacturing companies. Industry 3.0 evolved in 1969 with the concept of electronics, partial automation and information technologies. Industry 4.0 evolved in 2011 with the concept of smart manufacturing for the future. The main objective is to maximize productivity and achieve mass production using emerging technologies [2,3]. Industry 5.0 is a future evolution designed to use the creativity of human experts working together with efficient, intelligent and accurate machines [4]. Table 1 presents a summary of important surveys on Industry X.0.

1.1. Motivations behind the evolution of Industry 5.0

Industry 4.0 standard has revolutionized the manufacturing sector by integrating several technologies, such as artificial intelligence (AI), the Internet of Things (IoT), cloud computing, cyber physical systems (CPSs) and cognitive computing. The main principle behind Industry 4.0 is to make the manufacturing industry “smart” by interconnecting machines, devices that can control each other throughout the life cycle [22–25]. In Industry 4.0, the main priority is process automation,

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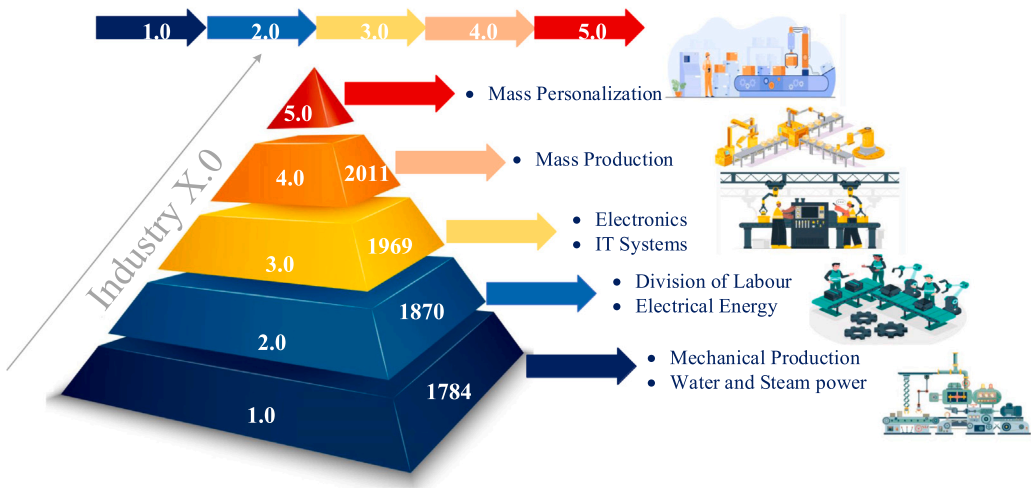

Fig. 1. Illustration of industrial evolution.

Table 1
Summary of important surveys on industry X.0.

Ref.	Industry 5.0 driving trends	Applications/Use cases	Requirements/Vision	Technical challenges	Enabling technologies	Ongoing activities	Research directions	Remarks
[5]	NA	L	M	M	L	L	M	Focused mainly on Industry 4.0 applications and challenges
[6]	NA	H	L	M	H	L	L	Focused mainly on Industry 4.0 health care applications
[7]	NA	M	L	M	H	M	H	Focused mainly on Industry 4.0 communication technologies
[8]	NA	L	L	M	M	L	L	Focused mainly on industrial communication for Industry 4.0
[9]	NA	L	M	M	L	L	L	Focused mainly on predictive maintenance for Industry 4.0
[10]	NA	H	M	L	H	H	M	Focused mainly on Industry 4.0 agriculture applications
[11]	NA	H	L	M	M	L	L	Focused mainly on security, fog for Industry 4.0 applications
[12]	NA	L	M	L	L	M	L	Focused mainly on security for Industry 4.0 applications
[13]	NA	L	H	H	M	L	H	Focused mainly on Industry 4.0 applications and challenges
[14]	NA	L	M	M	L	M	L	Focused mainly on blockchain in manufacturing systems
[15]	M	L	M	L	L	L	L	Focused on driving trends, requirements in Industry 5.0
[16]	L	L	L	L	L	L	L	Focused on modern technologies for Industry 5.0
[17]	L	H	M	L	L	L	L	Focused on use cases, technical investigations for Industry 5.0
[18]	M	H	L	L	L	M	L	Focused on driving trends, requirements in Industry 5.0
[19]	H	M	M	L	H	M	L	Focused on driving trends, applications, few enabling technologies in Industry 5.0
[20]	L	L	M	L	L	L	L	Focused on bionics, synthetic biology applications in Industry 5.0
[21]	M	M	L	L	L	M	L	Focused on Industry 5.0 in algae cultivation, customization
This paper	H	H	H	H	H	H	H	**A comprehensive survey of Industry 5.0 driving trends, applications, requirements/vision, technical challenges, enabling technologies, projects, research work, standardization approaches and future research directions**

L Low Coverage M Medium Coverage H High Coverage NA Not Applicable

thereby reducing the intervention of humans in the manufacturing process [26,27]. Industry 4.0 focuses on improving mass productivity and performance through the provision of intelligence between devices and applications using machine learning (ML) [28–30]. Industry 5.0 is currently conceptualized to leverage the unique creativity of human experts to collaborate with powerful, smart and accurate machinery. Many technical visionaries believe that Industry 5.0 will bring back the human touch to the manufacturing industry [31]. It is expected that Industry 5.0 merges the high speed and accurate machines and critical, cognitive thinking of humans. Mass personalization is another important contribution of Industry 5.0, wherein the customers can prefer personalized and customized products according to their taste and needs. Industry 5.0 will significantly increase manufacturing efficiency and create versatility between humans and machines, enabling responsibility for interaction and constant monitoring activities. The collaboration between humans and machines aims to increase production at a rapid pace. Industry 5.0 can enhance the quality of the production by assigning repetitive and monotonous tasks to the robots/machines and the tasks which need critical thinking to the humans.

Industry 5.0 promotes more skilled jobs compared to Industry 4.0 since intellectual professionals work with machines. Industry 5.0 focuses mainly on mass customization, where humans will be guiding robots. In Industry 4.0, robots are already actively engaged in large scale production, whereas Industry 5.0 is primarily designed to enhance customer satisfaction. Industry 4.0 focuses on CPS connectivity, while Industry 5.0 links to Industry 4.0 applications and establishes a relationship between collaborative robots (cobots). Another interesting benefit of Industry 5.0 is the provision of greener solutions compared to the existing industrial transformations, neither of which focuses on protecting the natural environment [32]. Industry 5.0 uses predictive analytics and operating intelligence to create models that aim at making more accurate and less unstable decisions. In Industry 5.0, the majority of the production process will be automated, as real-time data will be obtained from machines in collaboration with highly equipped specialists.

1.2. Contributions of this paper

There are numerous existing works that discuss the enabling technologies, applications and challenges of previous industrial standard (i.e., Industry 4.0) and the supporting industrial technologies [33–37]. For example, the authors in [34] study about the enabling technologies of Industry 4.0 standard as well as the reasons of their incorporation to the standard. At the same time, [33] discusses about the enabling technologies in Web of Science database for Industry 4.0 as well as the contributions of different forerunners (i.e., different countries and regions) in building this database. In [35], the authors provide an extensive overview on the enabling technologies of Operator 4 (i.e., the integrated standard for cyber physical systems and manufacturing process). Previously, in [36], the authors provided a survey work on the enabling technologies, applications and challenges of Industrial Internet (i.e., the integrated standard between Internet and industry). Virtual reality is another technological concept that has an ability to give a new height to the manufacturing process. Recently, the authors in [37] provided a thorough survey work on the enabling technologies and applications of virtual reality in IoT systems. Despite a growing trend in Industry 5.0, we are not aware of any review article that focuses on Industry 5.0. Motivated by this observation, we aim to provide a very first review on Industry 5.0. In a nutshell, the contributions of our work can be summarized asfollows [5–21].

- We first present various terms and definitions of Industry 5.0 from the available literature, which helps to deepen a clear understanding of Industry 5.0 from different perspectives.
- Secondly, we discuss a number of additional features of Industry 5.0 comparing with the previous industrial evolutions. Accordingly, the features of smart additive manufacturing, predictive maintenance, hyper customization and cyber physical cognitive system are discussed in detail. We also review the state-of-the-art projects, products, and standard development organizations related to Industry 5.0.
- Thirdly, we discuss the most promising applications to be developed and enabled in Industry 5.0, such as intelligent healthcare, cloud manufacturing, supply chain management, manufacturing production, and various other applications.
- Fourthly, we discuss key technologies of Industry 5.0, including edge computing (EC), digital twins (DT), collaborative robots, Internet of every things (IoE), big data analytics, blockchain, and future 6G systems and beyond.
- Despite several research and development activities, many challenges and issues are imposed in Industry 5.0. We finally present these difficulties in terms of security, privacy, collaboration activities among human and robots in a factory, scalability, and skilled workforce. We also highlight promising research directions towards the realization of Industry 5.0.

1.3. Paper organization

The remaining part of this article is organized as follows. In Section 2, we review the definitions of Industry 5.0 from the available literature, and characterize the added features of Industry 5.0 in comparison with previous industrial evolutions. The potential applications and use cases in Industry 5.0 are discussed in Section 3. The set of enabling technologies for Industry 5.0 are presented in Section 4 which include edge/cloud computing, Internet of everything, big data analytics, blockchain, 6G networks and beyond. In Section 5, we highlight the challenges and open issues relating to the research and development of Industry 5.0. Finally, we conclude this paper in Section 6.

2. Definitions and state-of-the-arts

The first industrial revolution has started in 1780 by generating mechanical power from different sources, followed by electrical energy utilization for assembly lines. Information technology has been employed to automate activities in the production industry. For example, the fourth industrial revolution utilized IoT and cloud to connect the virtual and physical space, later termed as CPS [38,39]. Though standard 4.0 changed the manufacturing industry, the process optimization ignored the human resources resulting in unemployment. Therefore, the industry pioneers are looking forward to the next revolution where both human intelligence and machines will be integrated for a better solution. The fourth industrial revolution aimed at transforming the manufacturing agents into cyber–physical systems (CPS) from complete physical systems through effective integration of business processes and production. This includes integrating all the entities in the manufacturing industry's supply chain, right from suppliers to production lines to end-users using IoT [40]. Industry 4.0 uses CPS to communicate with all the entities through the IoT network. As a result, the significant data accumulation is stored in a cloud environment for effective processing. Industry 4.0 uses technology concepts such as CPS, IoT, AI, Robotics, cloud computing, edge computing, big data analytics, ambient intelligence, virtual reality, and cybersecurity to achieve its central theme of Smart Manufacturing [41,42]. Industry 4.0 has reduced production, logistics, and quality management costs with increased mass production. Although Industry 4.0 has improved the manufacturing cost, it has ignored the human cost through process optimization. This inadvertently leads to the backward push of employment and will raise resistance from labor unions thereby affecting the full adoption of Industry 4.0 [32]. Industry 5.0 is expected to solve this issue through increased participation of humans.

With the rapid increase in environmental pollution from Industry 2.0, the manufacturing industry is focused on taking adverse effects to manage waste effectively and reduce its impacts on the ecosystem. Industry 4.0 does not ensure any environmental protection. Therefore, the need for a technological solution to provide pollution-free manufacturing processes has led to the next industrial revolution [5,43]. Industry 5.0 ensures the sustainability of civilization by reducing waste generation through bio-economy leading to a pollution-free environment. The fifth industrial revolution has focused on intelligent manufacturing by bringing back human intelligence to the production floor by enabling the robots to share and collaborate with humans. The Industry 5.0 has brought back the humans to co-work with machines (robots) on factory floors, thus utilizing human intelligence and creativity for intelligent processes [15]. Humans will share and collaborate with the cobots without fear of job insecurity, thus resulting in value-added services. This section provides definitions, features and state of arts of Industry 5.0.

2.1. Definitions

As Industry 5.0 is yet to evolve to the fullest, various industry practitioners and researchers have provided various definitions. Some of the definitions are discussed here.

Definition 1. Industry 5.0 is a first industrial evolution led by the human based on the 6R (Recognize, Reconsider, Realize, Reduce, Reuse and Recycle) principles of industrial upcycling, a systematic waste prevention technique and logistics efficiency design to valuate life standard, innovative creations and produce high-quality custom products [44] by Michael Rada, founder and Leader, Industry 5.0.

Definition 2. Industry 5.0 brings back the human workforce to the factory, where human and machine are paired to increase the process efficiency by utilizing the human brainpower and creativity through the integration of workflows with intelligent systems [31].

Definition 3. European Economic and Social committee states that the new revolutionary wave, Industry 5.0, integrates the swerving strengths of cyber–physical production systems (CPPS) and human intelligence to create synergetic factories [45]. Furthermore, to address the manpower weakening by Industry 4.0, the policymakers are looking for innovative, ethical and human-centered design.

Definition 4. Friedman and Hendry suggest that Industry 5.0 compels the various industry practitioners, information technologists and philosophers to focus on the consideration of human factors with the technologies in the industrial systems [46].

Definition 5. Industry 5.0 is the age of Social Smart factory where cobots communicate with the humans [47]. Social Smart Factory uses enterprise social networks for enabling seamless communication between human and CPPS components.

Definition 6. Industry 5.0, a symmetrical innovation and the next generation global governance, is an incremental advancement of Industry 4.0 (asymmetrical innovation). It aims to design orthogonal safe exits by segregating the hyperconnected automation systems for manufacturing and production [48].

Definition 7. Industry 5.0 is a human-centric design solution where the ideal human companion and cobots collaborate with human resources to enable personalizable autonomous manufacturing through enterprise social networks. This, in turn, enables human and machine to work hand in hand. Cobots are not programmable machines, but they can sense and understand the human presence. In this context, the cobots will be used for repetitive tasks and labor intensive work, whereas human will take care of customization and critical thinking (thinking out of the box).

2.2. Additional features of Industry 5.0

Industry 5.0 is the enhanced version of the fourth industrial revolution. The added features of Industry 5.0 are discussed in this subsection.

2.2.1. Smart additive manufacturing

The most popular cost effective approach for current manufacturing industries, which support producers to execute development plans, reduce pollution and resource utilization throughout the development lifecyle, is sustainable manufacturing [49]. Additive manufacturing is the sustainable approach adopted for industrial production, which builds the product part layer by layer instead of a solid block, thereby developing lighter but more robust parts one layer by layer. It adds up material layer by layer on the 3D objects. Smart additive manufacturing applies AI algorithms, computer vision to add more accuracy and better graphical representation of product design in 3D printing. Now, 5D printing, a new subset of additive manufacturing, is employed for better compositions. The recent enterprises and researchers are focusing on deploying smart manufacturing products in their research and industrial domain. With the recent advancement of technologies such as AI, IoT, Cloud computing, Big Data, CPS, 5G, DT, EC and manufacturing, smart empowering technologies are becoming popular and remarkably strengthened the development of smart manufacturing. Sustainability, profitability and productivity are the main advantages of smart manufacturing industry. From the last decade, smart additive manufacturing (SAM) has become emerging technology in smart manufacturing domain [50]. One of the prominent features of Industry 5.0 is additive manufacturing referred as 3D printing which is applied to make manufacturing products more sustainable. Additive manufacturing in Industry 4.0 focused on customer satisfaction by including benefits in products and other services. It also facilitates transparency, interoperability, automation and practicable insights [51]. SAM defines the various processes in which the component to be manufactured is developed by adding materials and the development is executed in various layers. SAM has capability to save energy resources, helps to reduce material and resource consumption which leads to pollution free environmental production. To obtain the complete benefits of Industry 5.0, SAM is merged with integrated automation capability to streamline the processes involved in supply chain management and reduces the delivery time of the products.

2.2.2. Predictive maintenance

As the economy of the world is moving towards globalization, the industries are facing many challenges. This is forcing the manufacturing units move to upcoming transformation such as predictive maintenance (PdM). To enhance the productivity and efficiency, the manufacturers started utilizing evolving technologies, such as CPS approaches and advanced analytical methods [52]. Transparency is the capability of industry to uncover and assess the uncertainties in order to estimate the manufacturing ability and availability. Basically, most of the manufacturing schemes assume the availability of equipment continuously. However, it never practically happens in the real industries. Thus, the manufacturing units should transform themselves to the predictive maintenance to acquire transparency. This transformation needs application of state-of-the-art prediction tools in which the data is processed to information systematically and defines the uncertainties to allow the manpower in taking smart decisions. The implementation of IoT provides the basic framework for predictive maintenance with the utilization of smart machines and smart sensor networks. Enabling self-conscious capability for systems and machines is the main goal of predictive maintenance. Smart computational agent is the key technology for predictive maintenance which includes smart software to provide functionalities for predictive modeling. In Industry 5.0, PdM helps to perform maintenance activity for avoiding problems instead of performing planned and scheduled maintenance and when a problem arises [9].

2.2.3. Hyper customization

Industry 4.0 targeted linking machines, created intelligent supply chains, promoted the production of smart products and isolated the manpower from automated industries. But Industry 4.0 has failed to manage the growing demand for customization whereas Industry 5.0 does it using hyper customization. Hyper customization is a personalized marketing strategy which applies cutting-edge technologies such as AI, ML, cognitive systems and computer vision to real-time data in order to provide more specific product, service and content to every customer. The integration of human intelligence with robots helps manufacturers to customize the products in bulk. In order to achieve this, many variants of the functional material is shared with other personnel with the motive of customizing the product with different variants for customers choice. Industry 4.0 aimed at huge production with low wastage and maximum efficiency whereas Industry 5.0 aims at mass customization with minimum cost and maximum accuracy. The collaboration between manpower and robots along with cognitive systems enable the industries to coordinate the processes in the manufacturing to implement the customer needs and market changes. The first step in hyper-personalization is transition to agile manufacturing process and supply chain. This also needs human intervention, production team and customer preferences. Also, the applicability of hyper customization depends strongly on the cost effectiveness of the developed products [53].

2.2.4. Cyber physical cognitive systems

Due to the advancement of technologies such as smart wearable devices, IoT, cloud computing and big data analytics, CPS has become popular now-a-days. The fourth industrial revolution has transformed the manufacturing process from complete manual systems to CPS [54, 55]. The framework for Industry 4.0 is established on the communication between CPS with the help of IoT. Cloud technology is used for huge amount of efficient, secure data storage and exchange [56]. Also, cognitive methods are used in several applications such as surveillance, industrial automation, smart grid, vehicular networks and environment monitoring to increase the performance of the system and thus called as cyber physical cognitive system (CPCS) [57,58]. Cognitive capabilities such as observe/study the environment and take actions accordingly are contained in the nodes of CPCS. Learning and knowledge are the primary components of decision making in CPCS. The CPCS has been introduced for human robot collaborative (HRC) manufacturing. The HRC executes the assembly of components in manufacturing division in collaboration with a robot and human. The integration of machine–human cognition is modeled and applied for this collaboration work in realtime. The fifth industrial revolution confined the merits of fourth industrial revolution and brings back the human labor for production. The fifth revolution facilitates the robots and skilled labor to work together in order to produce customized products and services in Industry 5.0 [59].

2.3. State-of-the-arts

This section discusses the state-of-art projects, products, investments, government policies and SDO.

2.3.1. Projects

The industries are moving towards this social smart factory era through the adoption of Industrial 5.0 technologies. Industry 5.0 mainly aims at waste management through industrial upcycling. Some of the notable projects of Industry 5.0 are discussed here.

Repsol- Intelligent management of resources and processes automation: Repsol is a multi-energy provider which leverages the technological advancements for building more sustainable energy models [60]. Repsol employs blockchain, CPS and robotic process automation technologies for enhancing security and productivity at its plants by alleviating the physical presence in dangerous sites through process automation systems. Furthermore, Repsol is applying Industry 5.0 in its upcoming projects to improve the working methods and environment (i.e. both hardware and software) through automation. Furthermore, Repsol develops advanced AI projects for recreating scenarios to optimize industrial processes.

The autonomous guided vehicle is the Repsol's first cobot with 100 kg of load capacity designed to carry out logistics activities among different plants like sample distribution between laboratories, waste disposition and delivery of raw materials from warehouse. This enables the lab virtualization, through which the practitioners can access and manage the equipment remotely.

The Block lab is an Industry 5.0 project by Repsol used to safely transmit sensitive or critical information through the blockchain's property of immutability and hash indices (certifying the originator). The Block lab is designed to streamline the samples management, where it creates digital equivalents of the samples for safety concerns, and it can effectively manage 10,000 samples per year.

2.3.2. Products

Industry 5.0 products have started to evolve in various domains like healthcare, food, cosmetics, consumer electronics, timber manufacturing, and so on. One of the products are discussed here.

Bundesgartenschau 2019: It is a wooden pavilion with a robot hand developed by the joint venture of Mullerblaustein Holzbauwerke, KUKA and Institute for Computational Design and Construction for timber construction [61]. The robots craft this wooden pavilion containing 400 elements. The robots bisect these elements from the wooden beams, correctly position the components, and assemble them to wrap with glue. KR 500 FORTEC robot is used in this product. This robot can perform all the carpenter tasks such as moving large components, assembling and applying adhesives, thus enabling the robotics and craftsmanship to collaborate.

2.3.3. Standards development organization

As Industry 5.0 is the evolving paradigm that makes a new revolution in the industry, to be accepted fully and to stay higher, it must adhere to globally accepted standards for its implementation. Compliance is an important issue in evolving regulations. This section provides the SDOs that initiated Industry 5.0 concepts and safety measures. International society of automation (ISA) is the first and principal organization for setting standards, guidelines, training and education for the industry professionals in automation to enhance operational excellence [62]. ISA aims to improve safety, streamlined component integration and to provide unswerving instrumentation. American national standards institute (ANSI), a non-profit organization that overseas consensus standards development worldwide has collaborated with ISA for developing standards for industrial control systems. ANSI and ISA have developed several standards pertaining to industrial control systems. It includes the standards for the use of graphical symbols in automation (ISA5), safety and practical application of the equipment in a hazardous environment (ISA12), specifications for different types of control systems (ISA88), practise for the alarm system in industrial processes (ISA18), the specification for using wireless systems in industrial automation (ISA100) [63], procedures for safe manufacturing control systems implementation (cybersecurity standard ISA99) and defines the standard interface for the integration automation control system and other enterprise activities (ISA95). Furthermore, it has developed standards for using programmable electrical or electronic devices for process safety (ISA84) and standard for promoting uniformity in instrument specification and manufacture (ISA20). International organization for standards (ISO) is a federation of national standards bodies worldwide. ISO technical committee (TC) has prepared the standards concerning robots at ISO/TC299 under Robotics. It is a safety standardization and provides safety standards for industrial robotics (ISO/TS 15066, ISO 10218-1 and ISO 10218-2) and non-industrial robotics (ISO 13482) sectors. Above all, the financial issues concerned with the maintenance of standards grow with evolving revolution.

3. Applications in Industry 5.0

This section discusses some of the potential applications of Industry 5.0, as pictorially explained in Fig. 2.

3.1. Intelligent healthcare

These days the doctors are using ML models to help them in diagnosing diseases of patients. This helps in improving the accuracy of diagnosis of diseases and hence saves lot of time and money for the patients [64,65]. However, this is not enough in the current scenario. A technology, that can ensure personalized requirements of a patient like monitoring measurement of blood pressure, sugar levels, etc., and give personalized treatment to the patients with assistance from the doctors is need of the hour. Industry 5.0 can make this possible. Intelligent wearable devices such as smart watches, intelligent sensors, etc. can constantly record the patient's health-care data in real-time and this data can be stored in the cloud. ML algorithms can then be used to diagnose the medical condition of the patents. These intelligent devices can communicate with each other and in case a doctor's attention is required, these devices can feed the current situation of the patient and alert the doctors to treat the patient. Through cobots, doctors can take help from the robots that can communicate with each other to perform surgery to the patients [66]. These are few examples of how Industry 5.0 can revolutionize healthcare industry. This revolution helps in manufacturing of personalized devices, implants, etc. Through Industry 5.0 routine jobs like routine checkups that are being performed by doctors can be taken care of by corobots. In this way doctors can concentrate on higher level of jobs. Even the complicated surgeries can be performed with precision by corobots with constant inputs from doctors. Technologies like DT can help the doctors to give personalized

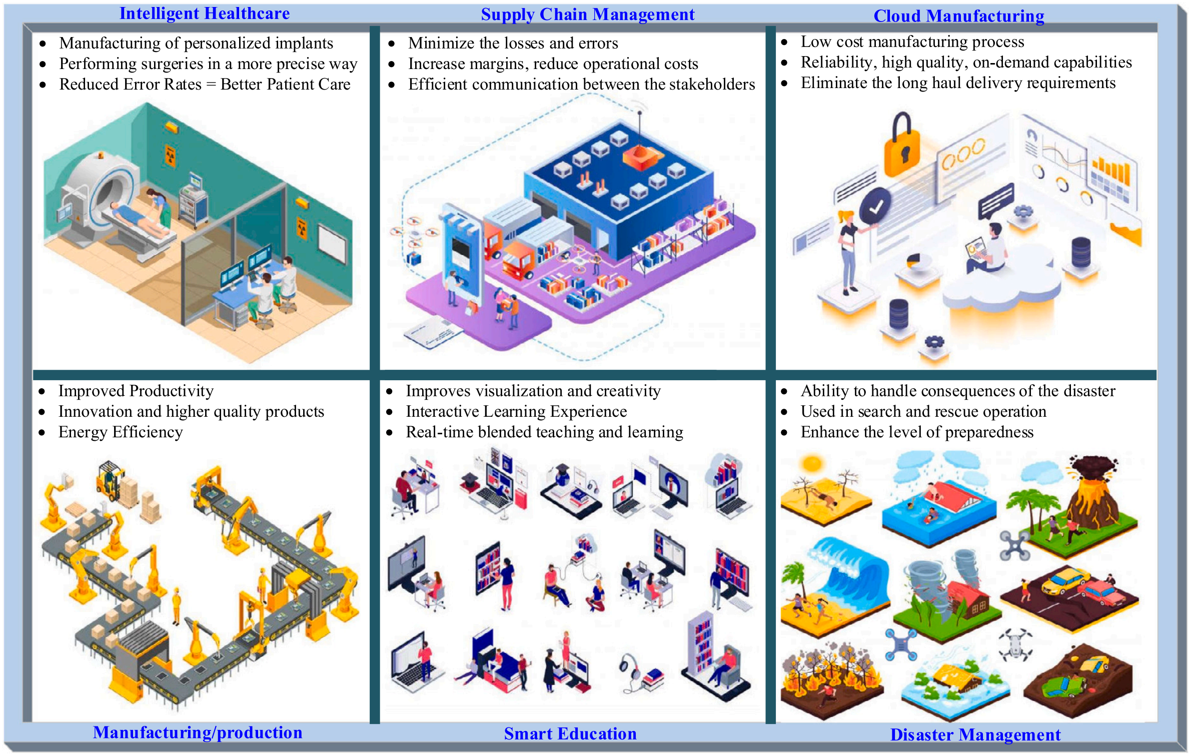

Fig. 2. Industry 5.0 applications.

prescription of drugs to the patients [67]. Rest of this subsection discusses about the recent research on potential applications of Industry 5.0 in healthcare.

Haleen et al. [68] suggest that Industry 5.0 can play a major role in manufacturing of personalized implants that can match the patients, which is the basic requirement in orthopaedics. They also suggest how Industry 5.0 can be helpful in performing surgeries in a more precise way. The authors also discuss the potential applications of Industry 5.0 in medical education sector. Javaid et al. [69] studied key enabling technologies in Industry 5.0 that can help in treating the patients during Covid-19 pandemic. They suggested how key enabling technologies in Industry 5.0 such as corobots can help in contact-less treatment of patients. They also suggested how intelligent robots with the help of doctors can help in scanning and treating Covid-19 patients, thus reducing the risk of exposing front-line healthcare to Covid-19 patients. Priadytmama et al. [70] have proposed the usage of assistive technology (AT), which was used for disabled or handicapped people, for everyone to provide higher individual capacity. They suggested that disruptive technologies in Industry 5.0 such as 3D printing can be helpful in realizing the usage of AT for many people. Through the aforementioned technologies, a wearable AT, like orthoses, limb prostheses, or exoskeletons, can be customized according to the geometry that can fit on the body parts of the user.

3.2. Cloud manufacturing

Cloud manufacturing is a novel way to revolutionize the traditional manufacturing paradigm in to an advanced manufacturing process by integrating latest technologies such as cloud and EC, IoT, virtualization and service-oriented technologies. In a cloud manufacturing process, multinational stakeholders will collaborate together to operate efficient and low cost manufacturing process. The distinguishing features of cloud manufacturing include reliability, high quality, cost effectiveness, and on-demand capabilities. In addition, it has positive impact on environment as cloud manufacturing can eliminate the long haul delivery requirements of raw materiel for the manufacturing process. Moreover, cloud manufacturing is leading advanced manufacturing models such as additive manufacturing and manufacturing grid as well. Fig. 3 illustrates the multinational collaborative nature of typical cloud manufacturing ecosystem.

Cloud manufacturing allows the designers to protect their intellectual components such as design files of manufacturing items by storing in the cloud with robust access control and utilize the manufacturing resources dispersed across different geographical regions [71]. In this manner, the designers are allowed to place their manufacturing plants closer to the raw material and also countries where manufacturing cost is cheaper. Here, the control of the machines in the plant and the operations of the manufacturing life cycle, such as service composition [72] and scheduling [73] are handled by the cloud. The working condition information of the manufacturing process can be collected via IoT sensors and analyzed in the cloud [74]. Li et al. [75] and Tao et al. [76] presented how cloud manufacturing can be deployed as a service oriented manufacturing model. Xu et al. [77] explained the potential business models in cloud manufacturing, including pay-as-you-go business model.

With Industry 5.0, the next generation of cloud manufacturing systems is expected to cater different and complex requirements in the engineering, production, and logistics contexts. The technological evolution of AI/ML technologies, EC features and 5G based telecommunication networks open up different avenues to expand the capabilities of future cloud manufacturing systems exponentially.

3.3. Supply chain management

Disruptive technologies that enable Industry 5.0 like DT, cobots, 5G and beyond, ML, IoT, EC, etc. aligned with the smartness and innovation of humans can help the industries in meeting the demand and delivering the personalized and customized products at a faster pace [78]. This helps supply chain management (SCM) in integrating mass customization, which is a key concept in Industry 5.0, into their production systems.

Fig. 3. The cloud manufacturing ecosystem.

DT can be used to create a digital replica of the SCM that consists of warehouses, inventory positions, assets and logistics. The DT encapsulates factories, suppliers, contract manufacturers, factories, transportation lanes, distribution facilities, and customer locations. DT supports in the entire life-cycle of the SCM, right from the design phase, to the construction and commissioning, to the operations [79,80]. Through simulating the real-time SCM systems, DT can sense the real-world data through IoT sensors. ML, big data, etc. can use these data to predict the difficulties faced during several phases of SCM. The industries can hence take pre-emptive corrective measures to minimize the losses and errors during several phases of SCM and can help in delivering customized products to the customers in quick amount of time [81]. With DT, businesses can evaluate the complex interconnected trade-offs in capacity, service, inventory and total landed cost. DT can also help industries in increasing their margins, reduce operational costs during several phases of the SCM. Some of the state-of-the-art works that present DT as a solution for SCM are discussed below.

Defraeye et al. [82] proposed a DT based approach that simulates mango fruit's thermal behavior throughout the refrigerated transport of the mango fruit. They have also developed an innovative sensing device that simulates the fruit to validate the fruit pulp's temperature model. The authors demonstrated how DT can provide insights into the thermo-behavior of fruits during the supply chain. These insights will help the SCM industry in identifying where the losses occur while transporting, temperature-dependent fruits and hence can take corrective measures to minimize the losses. In this way DT can help in improving logistics and refrigeration process to reduce losses and realize green supply chain. Grief et al. [83] proposed a concept of light-weight DT for construction industry. In this article they explored the benefits of DT in reducing the expenses of SCM in construction industry. Marmolejo [84] proposed a DT for a pharmaceutical company to make the SCM process more robust. The author has developed this technology by using solvers, simulators analytic tools. The author has modeled and analyzed Various operating scenarios of the inventory, supply, manufacturing, and product distribution process for a pharmaceutical company. DT has facilitated in predictive analytics that anticipates disruptions or changes in supply chain in pharmaceutical company and ensured better communication between the stakeholders.

Cobots can play a very important role in SCM. Tasks which are routine/dangerous such as packaging, routine quality checks, carrying of heavy goods, etc., that humans hesitate to do can be performed by robots, where as the expertise of the humans can be used in more complex jobs in the SCM life cycle [85]. Cobots can be used in applications throughout the lifecylce of SCM, such as material handling, assembly of the materials, packing, performing quality checks, transportation, delivery of the products to the customers and picking the return of the products from the customers. Through cobots, the SCM industries can reduce their total cost of ownership. Hence, cobots streamline all the processes in SCM, such as systematic inventory management, tracking of stocks, order fulfillment and return of the products [86].

3.4. Manufacturing/production

It is generally acknowledged that in past technological revolutions, the introduction of robotics and automation brought about paradigm changes in the manufacturing industry globally. Robots have historically done risky, monotonous or physically demanding work in manufacturing settings, such as welding and painting in car factories and loading and unloading heavy consignments in warehouses [87]. Industry 5.0 is aimed at combining these cognitive computing skills with human intelligence and resourcefulness in collaborative operations as machines in the workplace grow smarter and more connected. It is therefore conceivable that the fifth industrial revolution will bring shifts in norms and make fundamental changes in our approach to industry and manufacturing.

Nahavandi et al. [15] provided some practical implications as to how the fifth iteration could be seen in its realization state and its impact from productivity and economic point of view. This study also enlists the enabling technologies for Industry 5.0 which includes networked sensor data interoperability, multiscale simulation and dynamic modeling, production tracking, virtual training, autonomous systems, and machine cognition. They also suggested that the tasks of cobots in the fifth iteration will be to analyze the human intent before the analysis of the task itself, suggesting that the cobots should understand when its collaborative human needs help. The study suggests that we are still not anyway near to implementing Industry 5.0 as several industry leaders still believe in Industry 4.0 ideology. However, it was concluded that the fifth generation will create jobs in the field of human–machine interaction. Javaid and Haleem [88] identified significant indicators for Industry 5.0 for the application of manufacturing. Specifically, this study discusses the real manufacturing problems in association with 17 critical components of fifth industrial revolution. The authors suggested that the use of Industry 5.0 in manufacturing industries would surely add higher value for the company and increase customer satisfaction. Cary Sherburne [89] suggested the potential use of Industry 5.0 in textile industry. Their qualitative research provides a basis to use the characteristics of Industry 5.0 in fiber computing solutions which will eventually lead to its realization in textile industry soon enough.

3.5. Other applications

Education: Education is seen as a necessary necessity and the cornerstone for every country's reforms. In reaction to developments in both culture and business, education evolves, creating the valuable intellectual resources that businesses need in the future to succeed. The education in Industry 4.0 was more technological oriented i.e. minimizing human involvement and giving priority to machines but with 5.0 the motive is to create a synergy between autonomous machines and humans. The duo of powerful machines in combination with better-trained specialists will foster an effective, sustainable and safe production. Industry 5.0 will bring in the role of Lead Robotics officer. This individual specializes in machine–operator interaction, and also has experience in fields such as robotics and AI. His position in the organization requires making decisions on these variables and this is only possible with the education 5.0 skills i.e. fusion of technological and communication and leadership.

Kent and Kopacek [86] related the traditional education with Industry 5.0 by asking the questions such as whether the traditional education is enough to educate a worker? Or is there a need of improved education system? Their study transforms the human–machine interaction problem to cobot–coboters interaction where coboter is a human who works with the robot in a collaborative manner. This study also proposes an industrial proposal for cobot and coboters for working together on a specific task.

Human–cyber–physical systems: The fourth iteration focused on the provision of real-time interface between physical and virtual phenomena while leveraging the cloud computing and IoT concept, hence the name CPSs. The fourth iteration of industrial revolution was instigated from German government strategy project [90] with the intention to get best of both (physical and virtual) worlds in order to transform manufacturing agent. The critical issue in Industry 4.0 is the negligence of human cost in the process of optimization and efficiency improvement. Analysts have speculated that the said problem will increase and may face high degree of resistance from politicians and labor unions as Industry 4.0 progresses. The fifth iteration (Industry 5.0) has been proposed so that advanced technologies are continued to be used for efficiency improvement while tackling the aforementioned challenge. Chen et al. [59] focused on the human–cyber–physical systems for the fifth iteration of industrial evolution. The authors proposed the use of human–cyber–physical systems for future wind turbines. Although the study proposed the model on a conceptual level but it enlists the key enabling technologies such as structural health monitoring, information translators, and damage prediction models which can achieved through the integration of IoT, and AI based techniques. Longo et al. [91] highlighted the emerging issues in human–cyber–physical systems. The study conducted an administered survey from different companies and suggested that ethical technology and value oriented issues in factory environment does not need immediate attention. Furthermore, they proposed value sensitive design technique to design a framework which embodies human values and potential design steps for the factory of the future.

Disaster Management: Sudden, catastrophic incident that damages life or property is disaster and its prevention/management strategies are those that help us to reduce the consequences of the disaster. A core aspect of any corporate plan is catastrophe relief, but it only focuses on the short term. Many disaster recovery plans have been revised due to occurrence of COVID-19 pandemic, which possibly brings in the long-term resilience as a policy that replaces the disaster recovery strategies. Sukmono and Junaedi [92] proposed the use of fifth industrial revolution in the context of disaster management, specifically the one occurred in Indonesia 2018 having magnitude of 7.0. Their qualitative study revealed that Industry 4.0 faces limitations for disaster recovery and management systems. Moreover, integrating humans along with AI and IoT can help in solving the issues related to disaster mitigation. Also, not only earth quakes but other disasters such as pandemic can be efficiently managed through the collaboration of humans and intelligent machines.

4. Enabling technologies

Several enabling technological trends such as EC, DT, IoE, big data analytics, cobots, 6G and blockchain are integrated with cognitive skills and innovation that can help industries increase production and deliver customized products more quickly. These enabling technologies make Industry 5.0 an advanced production model with a focus on the interaction between machines and humans. Smart machines are designed to work collaboratively with human beings, and this collaborative work facilitates human capabilities more productive, exceptionally easy to automate for individuals and small businesses than ever before. A brief discussion on enabling technologies for Industry 5.0 is presented in this section. Fig. 4. highlights key enabling technologies in connection with Industry 5.0. Table 2 explains the role of enabling technologies in Industry 5.0 applications.

4.1. Edge computing

The rapid growth of the IoT and the provision of numerous cloud services have introduced a new conceptualization, EC, which enables data processing at the network edge. EC can offer significant value, not only in the future Industry 5.0 but also in the transition to Industry 4.0. EC is capable of meeting expectations related to latency costs, battery life constraints, response time requirements, data protection and privacy [93,94]. EC minimizes communication overhead and guarantees that applications are productive in remote areas. Additionally, EC has the ability to process data without passing it to the public cloud, thus helping to minimize security issues for the significant events in Industry 5.0. EC can perform some useful operations such as data processing, cache coherency, computing offloading, transferring and delivering requests [95]. With all these network operations, the edge must be designed efficiently to ensure security, reliability and privacy. For Industry 5.0 applications, EC ensures low latency, data security and privacy, and delivers efficient services to the end users [94]. EC provides real-time communications for next-generation Industrial 5.0 applications such as UAVs, autonomous vehicles [96] and remote patient monitoring. EC enables Industry 5.0 to use more accessible, standard hardware and software resources to access and exchange information related to their industrial sectors. In order to manage huge data, industries are trying to access data from local servers on a regular basis. One of the challenges of analyzing all these machines is that the amount of raw data is too large to be assessed efficiently. EC enables Industry 5.0 to filter data by minimizing the volume of data sent to a centralized server. In Industry 5.0, EC allows preventive analytics, which enables the preemptive detection of machine failure and mitigates this by enabling the manpower to make wise decisions.

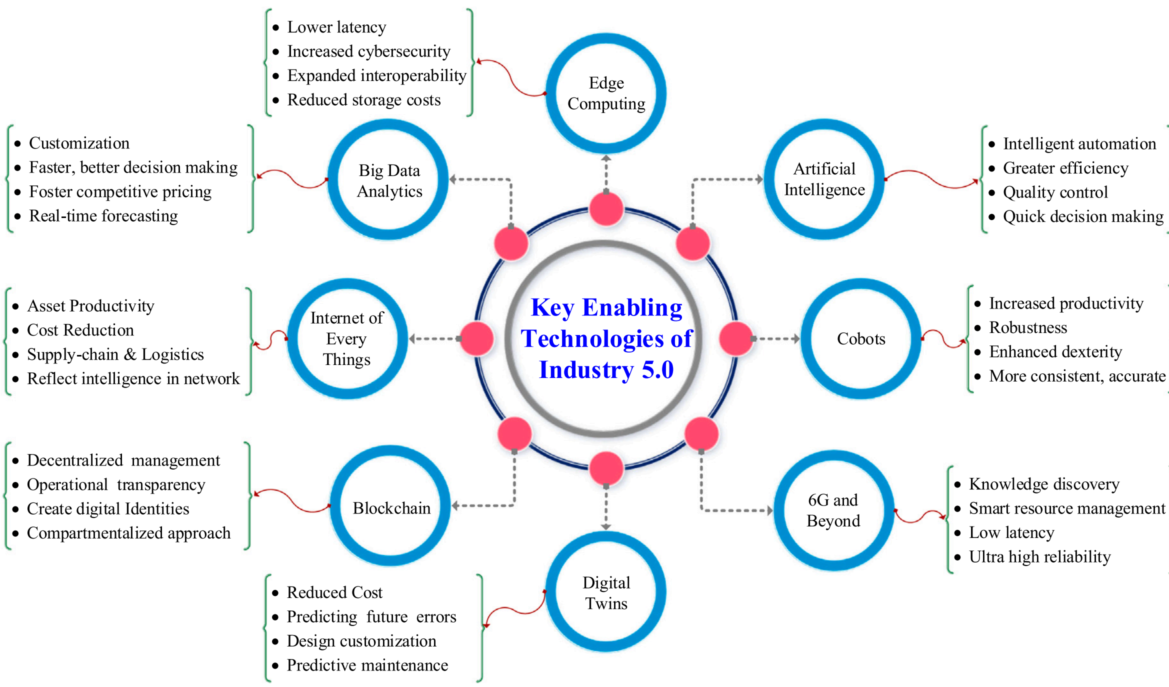

Fig. 4. Key enabling technologies of Industry 5.0.

Table 2
Role of enabling technologies on Industry 5.0 applications.

Industry 5.0 Applications	Enabling technologies											
	Edge computing	Digital twins	Cobots	IoE	AI	Big data	Blockchain	6G and beyond	Swam networking	Network slicing	Extended reality	Private mobile networks
Intelligent healthcare	H	M	L	H	H	H	H	H	L	H	H	M
Cloud manufacturing	H	H	H	H	H	H	H	H	H	H	H	M
Supply chain management	M	L	L	H	H	H	H	H	H	L	L	L
Manufacturing/Production	H	H	H	H	H	H	H	H	H	H	H	H
Education	H	M	L	M	M	M	M	H	L	H	H	M
Human–cyber–physical systems	H	H	H	H	H	H	H	H	H	H	H	H
Disaster management	H	M	M	H	H	H	M	H	H	M	H	M

H High Utilization M Medium Utilization L Low Utilization

4.2. Digital twins

A digital replication of a physical system or an object is called a DT. Real world objects such as wind farms, factories, jet engines, buildings or even larger systems such as smart cities can be represented digitally through DT [97]. Even though the concept of DT has been proposed in 2002, it has become a reality only in the last few years due to the surge of IoT. IoT made DT cost-effective thus making it accessible and affordable for many industries [98]. Through IoT devices, the data from the physical objects are fed to their digital counterpart for simulation. This mapping of real-time objects/systems digitally through DT makes it possible to analyze, monitor the digital version and prevent the problems before they occur in the real world. The rapid advancement of AI, ML, and big data analytics has enabled DT to reduce maintenance costs and improve performance of system [99].

In Industry 5.0, DT can offer significant value for the development of customized products on the market, enhanced business functions, reduced defects and rapidly growing innovative business models to achieve profits. The DT can enable Industry 5.0 to overcome technical issues by identifying them at a faster speed, identify items that can be reconfigured or renewed on the basis of their productivity, making predictions at a higher accuracy rate, predicting future errors, avoiding huge financial losses. This type of smart architecture design enables organizations to realize economic advantages successively and more quickly than ever before. In Industry 5.0, DT can be used to generate simulation models, access real-time computational data so that companies can remotely modify and update physical objects [100]. In Industry 5.0, DT is used for customization that can improve the user's experience of their product needs, a purchasing process that enables clients to build virtual environments to see the results.

4.3. Cobots (collaborative robots)

Recent trends in automation and robotics have made it increasingly important for people to work with robots. Due to the massive rapid changes in AI, smart technology, it is clear that all devices with computational capabilities have become more intelligent and have introduced a new technology called cobots. Collaborative robots are robots designed to work collaboratively with humans, and this collaboration helps to make human capabilities more efficient, extremely easy to automate for individuals and small businesses than ever before. The first cobots were developed by professor Edward Colgate and Michael Peshkin of Northwestern University in 1996 [101]. The first generation of cobots did not have motors and was also very passive in operation and had brakes during operation. Although today's cobots are very different from traditional industrial robots that have the ability to work with humans without enclosures. Cobots are usually embedded with sensors and are highly responsive to the detection of unpredictable impact, which gives them the ability to stop spontaneously when human workers detect any misplaced objects in their path. This tends to make them extremely reliable when it comes to safety at work compared to standard industrial robots [85].

Robots are extremely good in the manufacturing process of high-volume products and are much more compatible than humans. In comparison to human beings, robots are inefficient in critical thinking. Customization or personalizing of products may be a major challenge where robots require guidance. Managing human connections within production processes is therefore crucial. Cobots can offer significant value in Industry 5.0. Working with humans, robots can achieve their intended goal, thereby helping to deliver mass customized and personalized products to customers with high speed and accuracy. Personalizing of cobots can take many forms throughout Industry 5.0 by providing medical treatments, smart applications that efficiently summarize a patient's healthy life, and medical requirements to create a fully customized health fitness routine [85]. Surgery is one of the applications of cobots where a highly qualified doctor and a robotic assistant work together to perform surgery. Medical centers already enjoy the medical benefits of collaborative robotic-supported industrial processes. The Davinci surgical system is an innovation in cobot technology as it enhances the operating capability of surgeons in the surgery theater. Davinci cobot is widely used in urology and gynaecology surgeries, as well as in other surgeries. The role of cobots in Industry 5.0 is used to increase productivity and helps to build a new relationship between humans and machines. In Industry 5.0 applications, cobots help to improve safety and performance while at the same time facilitating more interesting responsibilities for human workers and increasing productivity growth [102]. Industries must realize that cobots offer not only the ability to improve business performance but also the potential to reduce rising labor costs in highly competitive markets.

4.4. Internet of everything

IoE is an interconnected link between people, processes, information and things [103,104]. IoE can provide significant value for the establishment of new opportunities for Industry 5.0 applications [105]. IoE's advancements in Industry 5.0 can create new functionalities, provide better experience and expected benefits for industries and nations. The role of IoE in Industry 5.0, enhancing customer loyalty and delight, building customization experience based on IoE-generated data. The use of IoE in Industry 5.0 provides an opportunity to minimize operating costs by eliminating bottlenecks on communication channels and reduces latency. Supply Chain and Logistics Efficiency is a challenging issue for Industry 5.0. IoE to minimize supply chain waste and optimize production processes. Due to the immense development of IoE, information sharing between humans takes place in wireless mode, essentially with the help of wireless sensors. For example, in the Internet of medical things, sensors are fixed to the patient. These sensors detect abnormalities in patients and transmit the sensed data to the doctor or nurse concerned. The physicians will take appropriate steps on the basis of the information obtained.

4.5. Big data analytics

Big data has recently become a major focus of discussion in both industry and academia [106–108]. It represents a large and diverse set of data collected from all types of sources. Many data analysis techniques include Big Data technologies such as ML, AI, social networking, data mining, data fusion, and so on [109,110]. Big Data Analytics tends to play an important role in the field of Industry 5.0. In Industry 5.0, some companies can use Big Data Analytics to better understand consumer behavior in order to optimize product prices, focus on improving production efficiency and help reduce overhead costs [111]. Understanding the current behavior of the user, social relations and human behavior rules is a critical challenge. Big Data Analytics is used by certain companies, such as Facebook, Twitter and Linkedin, which can help to promote products and increase sales on the basis of consumer satisfaction. Data infusion, massive customized manufacturing processes and smart automation in the production process are essential for the resolution of the Industry 5.0 ecosystem. Big Data Analytics can be used to make real-time decisions to enhance the competitive advantage of industries, with a focus on providing recommendations on predictive discoveries for major events in Industry 5.0 applications. In Industry 5.0, Big Data Analytics helps with mass customization processes with zero-fail integration with the available resources [112]. Real-time analytical data shared with smart systems and data centers helps manufacturers to produce and handle high data volumes. Continuous process improvement is another critical challenge in Industry 5.0, which often requires the collection of detailed information on the entire manufacturing cycle. Big Data Analytics techniques are used to recognize and eliminate non-essentialities to maximize predictability and explore new possibilities.

4.6. Blockchain

Blockchain technology can offer significant value additions in future Industry 5.0. Centralized management of a large number of heterogeneous connected devices in Industry 5.0 is a critical challenge. Blockchain can be used to design decentralized and distributed management platforms by enabling distributed trust [113]. Blockchain-enabled secure peer-to-peer communications offer an immutable ledger to keep records [95,114,115]. Moreover, the immutable ledger supports operational transparency and accountability for the significant events in Industry 5.0 applications. Especially, transparency is important for the dispute resolution in Industry 5.0 ecosystem [116]. The smart contracts can be used for security enforcement, such as authentication as well as automated service-oriented actions of the future Industry 5.0 applications. Also, a higher level of protection for data and transactions can be offered by using a compartmentalized and distributed approach using blockchains [117,118]. Data receiving and gathering [119] can also be enabled via blockchain.

Blockchain can be used to create digital identities for different people and entities in Industry 5.0 for efficient subscriber management. It is needed for access control and authenticating the stakeholders in any industrial activities over a public network [117]. Moreover, these digital identities can be further expanded to manage properties, possessions, objects and also services. Blockchain technology can also be used to register IP rights and to catalog and store original work [120]. Blockchains and smart contracts can also help to automate the contracting process by automating the agreement processes between different stakeholders. Moreover, blockchain-powered cloud manufacturing facilitates machine-level connection and data sharing based on blockchain technology [121,122].

4.7. 6G and beyond

In the future, 6G can offer significant value-added services to Industry 5.0. Radio infrastructure with a very dense chain of thousands or millions of sensors, hardware elements and robots is a challenge. With the vigorous growth of smart infrastructure and potential applications with current networks (e.g. 4G and 5G networks), it will not be possible to meet rapidly increasing bandwidth requirements. The use of 6G and beyond in the Industry 5.0 revolution makes it possible to deliver better latency, support high-quality services, as well as extensive IoT infrastructure and integrated AI capabilities [123]. In Industry 5.0 applications, 6G networks help improve application performance efficiently and effectively by providing smart spectrum management, AI-powered mobile EC, and smart mobility [124,125]. For Industry 5.0 applications, 6G networks are expected to meet the standards of an intelligent information society that can deliver ultra-high data rates, ultra-low latency, ultra-high reliability, high energy efficiency, traffic capacity, etc. Mobility and handover management are the most significant challenges for 6G networks in Industry 5.0. The 6G networks will be large-scale, highly dynamic, multi-layer networks that lead to frequent handovers [126,127]. AI techniques can be used to obtain optimal mobility predictions and optimal handover solutions to ensure efficient connectivity [128]. The greatest challenge for Industry 5.0 applications is to provide a high data rate for different applications. Quantum communication and free-space optical communication in 6G can fix these issues. In Industry 5.0 applications, a large number of smart devices are connected and an excess amount of energy is consumed therefore energy management is a critical challenge in Industry 5.0. 6G networks optimize energy management through the use of advanced energy consumption strategies and energy harvesting methods.

4.8. Other enabling technologies

In addition, some of the existing technologies such as Network Slicing (NS), eXtended Reality (XR), and Private Mobile Network (PMN) play a vital role in enabling Industry 5.0 and its applications.

NS concept allows enabling multiple virtualized networks on top of a single physical network infrastructure. It slices physical network resources across these virtualized networks [129]. Each virtualized network can be optimized and tailored to satisfy the requirements of different vertical applications. In this aspect, NS plays a vital role in enabling different Industry 4.0 applications [130,131] and will be important in Industry 5.0 as well. Since Industry 5.0 supports a diverse set of applications, one physical infrastructure will not be capable of fulfilling heterogeneous network requirements. NS can offer different virtualized networks cost-effectively. In [132,133] and [134], authors present a way of using NS for self-organization, flexibility and optimal network resources utilization for network monitoring in IIoT networks. In the future, advanced slicing techniques such as federated slicing, hierarchical slicing, and zero-touch slice automation can play an effective role in the realization of Industry 5.0 applications [130,135].

XR is an another emerging technology which is used in many application domains [136]. XR can improve human–machine interactions by combining virtual and physical worlds [124]. XR is representing a mixture of Virtual Reality (VR), Augmented Reality and Mixed Reality (MR) technologies [137]. XR technologies will play a vital role in enabling different Industry 5.0 applications. XR technologies are already using in Industry 5.0 related applications such as remote assistance [138,139], assembly line monitoring [140], health education/training [141], remote healthcare [142], indoor and localized outdoor navigation [143–145], driver/pilot training [146,147], maintenance [148], drone/UAV pilot training [149] and education [150]. Zero touch networking, edge computing, high capable devices, enhanced communication technologies and high precision computation capabilities will be important to further development of XR technologies towards Industry 5.0 applications [16,151].

The introduction of the network softwarization concept in 5G has eliminated the requirement of dedicated, expensive, and vendor-specific hardware equipment to build mobile networks. Thus, network softwarization enables the possibility to deploy local or private mobile networks [152]. Contrary to the traditional country-wide Mobile Network Operators (MNOs), PMNs are deployed to deliver localized, use case-specific network services. With 5G, Local 5G Operators (L5GOs) can be used in several Industry 5.0 applications such as factories [153,154], hospitals [155,156], schools and universities [157] to deliver location-specific connectivity solutions. The integration of NS, AI and blockchain technologies would optimize the deployment of PMNs for Industry 5.0 realization [158,159]. Moreover, regulation, management, and leasing of spectrum for PMNs should also be studied further for cost-efficient deployment and wide adaptation for Industry 5.0 deployments [160].

5. Lessons learned and future research challenges

This section discusses the lessons learned from the current state-of-the-art studies, and based on these lessons, synthesizes the future research challenges that need to be addressed to pave the way for a efficient Industry 5.0 ecosystem.

5.1. Lessons learned

Industry 5.0, from its evolution, has been adopted in most industries, ranging from biological sciences, retail, manufacturing, health care, and textile, dentistry and finance. An implication in [161] suggests that Industry 5.0 has a more significant target in fusion energy in a geopolitical context. In this section, a brief discussion on the lessons learned from various state-of-the-art studies, applications and their enabling technologies on Industry 5.0 is presented.

5.1.1. Definitions of Industry 5.0

From the definitions stated by the researchers, it is observed that Industry 5.0 is not an evolution; it the next industrial revolution where humans and robots co-work. The significant implication lies in matching human intelligence with machine intelligence and training the cobots to adapt to a sweeping change of the human brain while co-working. So, human intelligence can be applied for critical thinking of the customization logic, and the cobots can be utilized for labor-intensive tasks, thereby, alleviating the weakened manpower by effective use of cobots for labor-intensive jobs. Furthermore, SAM ensures reduced energy resource consumption through its layered manufacturing capabilities, and proactive PdM enables more manageable maintenance and a faster recovery rate in case of failures. The personalized manufacturing solutions through AI and cognitive systems for every customer will be assured by hyper customization throughout the manufacturing processes. CPCS employs cognitive skills in almost all the activities where the human and the cobots collaborate for delivering seamless services to the customer. Moreover, the current projects in Industry 5.0 guarantee that AI optimizes the industrial processes leading to more customized and faster-performing products. Though Industry 5.0 is in adoption, global standards and policies are still evolving to make it an international standard.

5.1.2. Industry 5.0 applications

Based on the observations from several state-of-the-art, Industry 5.0 is already in practice in several sectors like healthcare, cloud manufacturing, supply chain management, manufacturing/production, education, human–cyber–physical-systems, disaster management, etc. In addition to integrating several latest technologies like AI, IoT, edge computing, cobots, 6G and beyond, digital twins, big data analytics, etc. with the machines, the intelligence of the humans is also used in Industry 5.0 when making decisions. Hence, the personal human touch is added along with the pillars of Industry 4.0 like efficiency and automation [162,163]. The human–robot co-working ability of Industry 5.0 utilizes the intelligence and decision making of humans, supported by key-enabling technologies, helps in achieving mass personalization like never before across several sectors. Even though Industry 5.0 has a huge potential in revolutionizing several industries/sectors, there are several challenges that have to be addressed like handling of heterogeneous data, resource management, handling of huge quantity of data, latency, etc. to realize its potential fully.

5.1.3. Enabling technologies

According to the current state-of-the-art, Industry 5.0 plays a significant role in a variety of applications by adopting enabling technological trends such as EC, DT, IoE, big data analytics, cobots, 6G, blockchain, NS, XR, and XR PMN. All these enabling technologies are integrated with cognitive skills and innovation that can help industries increase production and deliver customized products more quickly.

- The advancements of EC have enabled Industry 5.0 to minimize latency, reduce network bandwidth, improve overall data security and privacy, and facilitate transactions that are hampered by connection issues. EC helps Industry 5.0 to use standard hardware and software resources to exchange information about their industrial sectors.
- The DT helps Industry 5.0 to overcome technical problems by recognizing them faster, identifying items that can be reconfigured or renewed based on their productivity, making more accurate predictions, predicting future errors, and avoiding large financial losses.
- In Industry 5.0, cobots are used to increase productivity and reinforce a new relationship between humans and machines. Cobots improve safety and performance in Industry 5.0 applications while also allowing for more interesting responsibilities for human workers and increasing productivity growth.
- The role of IoE in Industry 5.0 provides an opportunity to reduce operating costs by eliminating bottlenecks on communication channels, reducing latency, reducing supply chain waste, and optimizing production processes.
- Big Data Analytics aids in mass customization processes in Industry 5.0 by ensuring zero-fail integration with available resources. Real-time analytical data shared with smart systems and data centers assist manufacturers in producing and managing large amounts of data.
- Blockchains and smart contracts are being used to automate the agreement processes between various stakeholders and add dynamicity to the contracting process. The smart contracts are used for security enforcement, such as authentication and automated service-oriented actions for Industry 5.0 applications.
- For Industry 5.0 applications, 6G networks are expected to meet the standards of the intelligent information society that can deliver ultra-high data rates, ultra-low latency, ultra-high reliability, high energy efficiency, traffic capacity, etc.
- NS provides different virtualized networks at a low cost and optimal network resource utilization for network monitoring in IIoT networks. XR are used in Industry 5.0 applications like remote assistance, assembly line monitoring, health education, remote healthcare, indoor and localized outdoor navigation, driver/pilot training, maintenance, and drone/UAV pilot training. PMNs are used to deliver localized, use case-specific network services, used in several Industry 5.0 applications such as factories, hospitals, schools, and universities to deliver location-specific connectivity solutions.

5.2. Discussion on Industry 5.0 potentials

A study on Industry 5.0, its integration with AI, Big-data and IoT was presented in [48]. They suggest building safer and complicated hyper-connected networks that can be the future of many domains, such as a digital drugs to monitor real-life drug adherence. Big data accumulations in many digital environments will also benefit from AI, IoT, and Industry 5.0. Furthermore, the prospective applications of Industry 5.0 in coronavirus disease (COVID) for providing personalized therapy and diagnosis to the patients was presented in [164]. They have used Industry 5.0 technologies (like holography, 4D scans, humanoid robots, telemedicine and smart inhalers) for supporting COVID pandemic. They suggested the significant challenges that can be taken up by Industry 5.0 (such as tracking patients, automatic personalized treatment, optimize the supply chain, digital medicine, drugs manufacturing, creating awareness, and crowd monitoring) in solving the problems related to effects of COVID pandemic. Also, in the post-COVID era, the advent of cobot, CHIPBOT (implanted chips in COVID patients) and CURBOT (currency and bankless systems) can be utilized for making contactless payments, tracking of kidnappers, monitoring and treating the patients.

A value-sensitive design for the smart factories was proposed in [165]. It discusses the potential of Industry 5.0 in the future industry by human–machine symbiosis. Also, the machine's ethical implications on human workers in industrial systems engineering were presented with solutions and illustrated how the value-based design mitigates the issues concerned with the implementation of the symbiotic Industry 5.0. Absolute innovation management framework developed in [166] suggests the better understanding of innovation ecosystem, corporate strategy and design thinking for the managers to address the IoT and Industry 5.0 needs. But the study does not address the implementation perspective of the framework and safety measures upon integration with business processes.

A study on critical components of Industry 5.0 and its benefits compared to its predecessor was carried out in [167]. The study suggests that Industry 5.0 enables smart manufacturing through intelligent data usage through the interconnection of multiple factory data and advanced technologies, thereby producing more customizable products. The developed processes and technologies fasten the process by enabling the machines to handle conventional repetitive tasks and human cognition for innovation. Furthermore, the use of renewable resources and a lean innovation approach [168] for waste management , Industry 5.0, positively impact the environment.

A survey in [169] has presented the prospects of Industry 5.0 in algae biorefinery, that can customize the algae production, and enable real-time algae growth monitoring, thus reducing the operational costs. The customization of bioenergy (solid, liquid and gas biofuels) production and tools, medium and constraints for algae cultivation using Industry 5.0 is presented. Like [167], this study confirms Industry 5.0 will maintain the positive environmental impact without affecting the marine resources through effective application of AI models.

As the better solutions for traffic management issues in transportation still prevails, Industry 5.0 can provide remarkable advancement in the sector by utilizing human intelligence, machine smartness with 5G networks and other technologies. Industry 5.0 can integrate smart technologies to communicate and collaborate, designing a more intelligent autonomous vehicle. Apart from this, the textile industry will also benefit more from this revolution, providing customers with more personalized costumes. Industry 5.0 can use fiber computing [170] for more customized products, consequently leading to more sustainable textile manufacturing. Therefore, Industry 5.0 has a wide range of applications in almost all domains to serve the customers with more personalization.

5.3. Future implementation challenges

Industry 5.0 can empower the most customized services to the customer through the cognitive enabled manufacturing process. For seamless services, some of the potential implementation challenges discussed in this section must be addressed. One of the potential challenges is security. As we move towards more digitized computation, the security vulnerability must be cross-checked in heterogeneous data handling and utilizing cloud services for varied user and industrial data management. Also, privacy-preserving data transactions, privacy in data accumulation, and ethical issues must be pondered while offering customized and more predictive services to the customer. Bringing back man-force to the factory floor may be effective but practical issues and compliance in neighboring the human intelligence with the machine and vice versa must be accommodated with effective training for both. The problems concerned with scaling up the users and the manufacturing processes must be accounted for customized customer support with human–robot co-working. Furthermore, the ethical issues involved with AI adoption must be considered, thereby avoiding potential drawbacks and negative societal impact upon its success.

5.3.1. Security

Industry 5.0 will face critical security issues during the deployments. Similar to the tradition CPSs, Industry 5.0 will also need to provide security needs such as integrity, availability, authentication, and audit aspects [171].

- **Authentication:** The authentication of massive number of different stakeholders such as IoT nodes, machines, fog nodes, communication nodes and collaborative partner nodes is critical requirement to establish the mutual trust in the ecosystem. The authentication mechanisms used in Industry 5.0 should be scalable to connect billions of devices, quantum resistance to stand against future quantum computing applications and lightweight to deploy with IoT nodes [172].
- **Integrity:** The integrity is a primary concern in the perspective data security [77] in Industry 5.0 as controlling commands and monitoring data will be transferred over third-party networks. However, the integrity validation must not affect the performance features in the system.
- **Access control:** The establishment of access control mechanisms is an essential security measure in the future Industry 5.0 ecosystems to ensure that access to the sensitive resources such as intellectual properties restricted only to authorized stakeholders. The establishment of access control mechanisms with the demand expansion is challenging in most of the computing implementations.
- **Audit:** Auditability is a primary consideration to evaluate the alignment of service operation along with the regulatory compliance definitions. Furthermore, the audit logs require to investigate dispute resolution cases. The log management in Industry 5.0 must support the scalability requirements in the massive connectivity anticipated in the future Industry 5.0 systems.

The use of AI and supporting automation in Industry 5.0 will open up a new threat vector. For AI/ML functions, it is important to have trusted execution for security. Specially, the integrity of data set used for ML model training and also AL algorithm should be protected for proper operation in Industry 5.0 applications [173]. For instance, different tenants in Industry 5.0 should securely share empirical data for AI model training or incremental model updates as in federated learning. Also, the significant Industry 5.0 applications are highly dependent on ICT systems that will lead to new security requirements such as deployment of proactive security mechanisms [174,175] and mitigation of Zero day attacks [176,177]. Moreover, the development of quantum computing, may lead Industry 5.0 to operate in Quantum computing era. The protection of legacy security mechanisms will be dramatically simplified by a quantum computer [178]. In that case, Industry 5.0 systems should utilize quantum resistant cryptography or post-quantum cryptography mechanism to provide required level of protection [171].

5.3.2. Privacy

As the entire Industry 5.0 ecosystem functions with expensive intellectual assets, expensive manufacturing materials, subscription management, privacy is a vital requirement of Industry 5.0 applications [179]. In Industry 5.0, the data is exchanged over the Internet to connect machines with humans, designers with other collaborators and also to exchange monitoring and control information. Such data must not be visible to the malicious users in the Internet to ensure the trust of cloud manufacturing ecosystem [180].

Upon implementing AI, specific societal and ethical implications should be adhered to avoid the negative societal impact. It is common for a human labor to think that AI may lead to the displacement of their jobs, but Industry 5.0 will increase the job opportunities. The ethical issues with AI [181] and its impact on humans must be alleviated for the seamless collaboration of humans with cobots for co-production. The social choices, ethical values, relations, and cultural patterns must be integrated into cobots [182]. The policymakers for the industrial revolution must account for the ethical issues concerned with the human on human–machine coworking. The privacy issues include human data protection rights, i.e., humans have control over their data. They have the right to claim for any data theft incurred on their private and sensitive information. Therefore data privacy must be ensured by safeguarding the user data [183] while using it for cognitive analysis for predictive maintenance.

Blackbox AI is an automated decision-making system using ML over a large volume of data that maps the features for predicting the individual's behavioral traits without exposing the reason behind the analysis) The issues concerned with Blackbox AI, i.e., lack of transparency observed with the increase in AI adoption from the dawn of the fourth industrial revolution, must be considered upon its integration with human intelligence [184]. Sometimes, a faster production process may lead to overproduction and wastage of goods [15]. So implementation transparency should be accounted. Though the explainable AI (that expands human intelligence) does not replace humans, gaining human trust in AI applications (making crucial decisions) is wearisome [185]. Explainable AI should be embarked to pursue enhanced trust in AI systems through transparent AI systems. Therefore, privacy should be adapted as a design concept to ensure AI-based systems' steady progress with powerful predictions. Although many enterprises are still struggling to implement Industry 4.0, the dawn of Industry 5.0 will be even more challenging. Blockchain is a distributed ledger technology that is transparent, immutable, decentralized, and records the information in a more secure way [186]. Also, it is more resource-consuming as it requires more energy for mining the data at its nodes. But it ensures the security of the data through digital hashes of the previous records. Blockchain can add a significant contribution to security and privacy issues in Industry 5.0. Since the blockchain is resource consuming, when the number of nodes in the blockchain-based Industry 5.0 applications increase, it may slow down. So to avoid this, a lightweight blockchain framework can be deployed by segregating the rarely used information from the blockchain to its sidechain. Furthermore, quantum computing can be used for securing the CPS [187] or CPPS without any downtime.

5.3.3. Human–robot co-working in factory

Industry 5.0 brings back the human to the factory floor, where human and Cobot will be working as a companion. Though it seems to be an efficient way to develop personalized products, certain issues concerned with the co-working of humans and robots must be considered. Also, the fear of losing jobs among humans will be alleviated when both the robots and human shares the work. The cobot will take care of the repeated activities, thereby allowing the human to put full effort in creativity and innovation. Cobots complementing humans will be better, whereas the vice versa may create chaos in organizational behavior and may complicate the prevailing corporate culture of position competition. This may bring varied issues such as changing the role of human resources, IT departments with robotics, ethical problems associated with cobots, training the human to compete with cobots, regulatory issues, psychological concerns to make human adopt for a new way of working, and task dynamics analysis to human as well the cobots [188]. Furthermore, human working with cobots are skilled and may expect more than a typical job culture.

5.3.4. Scalability

Scalability can be expressed in terms of the system's resilient nature, flexibility, and responsiveness when the system's workload changes dynamically. In terms of Industry 5.0, when the number of hyper-connected systems in the network increases or decreases, the scalability is the system's performance at different working conditions. Industry 5.0 is meant to connect and communicate with numerous systems from other factories and several human beings. As Industry 5.0 is an advancement of Industry 4.0, scalability is one of its property, but it is a more significant challenge when making the robots or machine, and human a companion by sharing their workload [189]. The scalability can be tracked up using service level indicators validated as per the service level objectives specified in service level agreements. Furthermore, this is an essential concern because of the growth of data accumulation, machinery, factories, and human is non-deterministic. To ensure scalability, the Industry 5.0 environment's technology makers must be available for offering service at any workload, flexible enough to stretch and scale, and provide a low-latency response without any data processing delays. AI-based cobots must be capable of processing the numerous queries obtained from the flexible cloud and dynamic edge servers without any unprecedented delays.

Additive Manufacturing (AM) Scaling: During production, the thousands of printers might be working on the same capability and may be intended to same part order; in such cases, AM should scale itself with automation environment and changing needs. AM allows on-demand manufacturing without any conventional constraints to develop more customized products with less lead time. They are specific issues about AM scaling [190]. One of the problems is the path identification for utilizing AM results and scaling them for production use. The second issue is identifying the hindrance for AM scaling into production and mitigation techniques. The third issue is AM scaling with future trends and changing markets. The counterproductive based on demands can promote AM scaling. The issues concerned with AM scaling in production can be enhanced by utilizing 4D or 5D printing capability can be utilized with efficient software for designs. Also, AM scaling industry standards must be refined and should be defined for the industry-wide application of AM. As the data accumulations on the cloud server increase, the data processing can cause unprecedented delays leading to delayed response. Henceforth, the EC with AI can be integrated at the network edge devices through micro data centers. As discussed earlier, EC will reduce the delays ensuring low latency responses and the AI will make data predictions at the edge, thus making the edge device a cognitive edge.

5.3.5. Skilled workforce

As a skilled worker in Industry 5.0 is expected to deliver a high-value task in production, standardization and legal policies must be enforced to handle any technology, society, and management issues. Imparting a skilled workforce includes various concerns with management, employees, company culture, management infrastructure [191] and standard policies. The major challenge concerned with skill space is inadequate trainers and financial constraints in affording proper training to the humans co-working with cobots. By the time Industry 5.0 is fully adopted, the requirement of a skilled workforce will be more as well new technologies will grow, leading to adequate training for both the trainees and the prospective trainers. This may foster public–private partnerships [192]. Also, regulatory reformation will be a mandate. Furthermore, organizational excellence can be empowered by the trained workforce.

To be on par with digital competence, many industries would adapt to the newly developing technology, but management might not be understanding it. The skilled employees and the culture may exploit the management's ignorance. Furthermore, it will incur considerable training costs from a management perspective if the employees are not forward thinkers (the senior employee may take longer to adapt) and may take time for reengineering. Moreover, some companies may have inadequate infrastructure to accommodate the new technology. Therefore these issues must be considered while setting up an open business culture and sustainable recruitment of skilled employees. This, in turn, will amend the future business transformations at a faster pace. Continuous and effective training to both the human and the cobot will avoid most of the co-working issues. Furthermore, continuous training for operational workers (human workmanship) will ensure a skilled workforce.

5.3.6. Regulatory compliance

The major requirement for full adoption of any industrial revolution is laws and regulations. Although standards for automation, innovation policy and industry policies are available in general, the more specific standard for this new era must be enforced. As Industry 5.0 aims to bring back the human workforce to share and work together with cobots and smart machines, various regulations pertaining to both the human and cobot must be devised [193]. Several issues may arise without proper regulations and legal policies in this co-production environment [32]. Regulations for distinguishing cobot from other machines like drones must be enforced. Also, regulations which will inculcate use of AI, cobots, other machines in manufacturing industry should be devised for better predictions and sophistication co-production. The better standards, laws, guidelines and standards will make the adoption faster, complete and more manageable.

Therefore a robust framework for Industry 5.0 must use blockchain and quantum computing for the security and data preserving data transactions and cognitive edge for faster data processing with sub-second latency. AM, the so-called 3D printing has been employed in almost applications and AM scaling remains the most pertaining issue. Various potentials of Industry 5.0, their challenges and future directions are shown in Table 3 and Fig. 5. Apart from AM scaling, other scalability issues concerned with manpower and other resources need to be addressed effectively.

6. Conclusion

In this work, we presented a survey-based tutorial on supporting technologies and potential applications of Industry 5.0. We started this work by providing the definition of some concepts of Industry 5.0 from the perspective of both industrial and academic communities. We later discussed some of the potential applications of Industry 5.0 such as intelligent healthcare, cloud manufacturing, supply chain management, manufacturing production, etc., followed by the discussion on key-enabling technologies of Industry 5.0. In summary, Industry 5.0 is a concept that has been designed to harmonize the working space and efficiency of humans and machines in a consistent manner. Enabled by a variety of emerging applications and supporting technologies, Industry 5.0 is expected to increase manufacturing production and customer satisfaction. We also presented a number of challenges and open issues like security, privacy, human–robot co-working in a factory, scalability, and skilled workforce that should be handled to better realize the concept of Industry 5.0 in the near future.

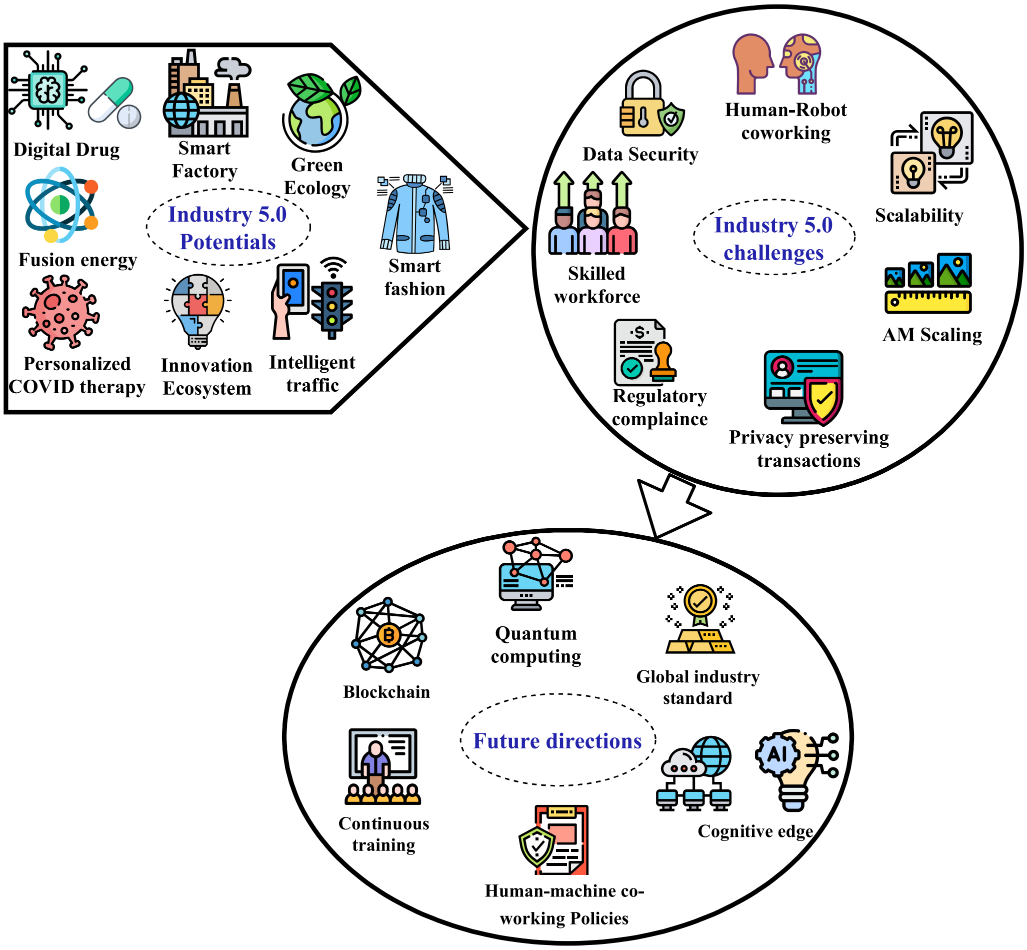

Fig. 5. Industry 5.0 potentials, challenges and future directions.

Table 3
Industry 5.0 potentials, challenges and future directions.

	Industry 5.0 Challenges							Future Directions					
Potentials Industry 5.0 Applications	Data Security	Skilled Workforce	Regulatory compliance	Privacy Preserving Transactions	AM Scaling	Scalability	Human Robot Coworking	Blockchain	Continuous Training	Human-Machine CO-working Policies	Cognitive Edge	Global Industry Standard	Quantum Computing
Digital Drug	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓
Fusion Energy	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓
Personalized Covid Therapy	✓	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓
Innovation Ecosystem	✓	✓	✓	✓	X	✓	✓	✓	✓	✓	✓	✓	✓
Intelligent Traffic	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Smart Fashion	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Green Ecology	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Smart Factory	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Declaration of competing interest

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

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