Discover Sustainability

Review

A comprehensive review on the impact of Industry 4.0 on the development of a sustainable environment

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Abstract
The application of Industry 4.0 technology has substantial prospects for future innovation and corporate growth. This research study investigates the influence of Industry 4.0 technologies on the establishment of environmental sustainability in the manufacturing sector and other associated industries. Industry 4.0 and its associated technologies, including the Internet of Things (IoT) and cyber-physical systems, have a detrimental effect on environmental sustainability. This is due to factors such as air pollution, improper waste disposal, and excessive consumption of raw materials, information, and energy. The approach employed in this study is an extensive review of a literature review comprising 207 manuscripts that explore subjects pertaining to Industry 4.0 and environmental sustainability. Currently, there is a gap between the current and intended state of affairs. Production is happening in a paradigm that lacks sustainability, which is why this research examines the impact of Industry 4.0 on environmental sustainability and the relevant aspects of Industry 4.0. One of the objective of this study is to examine the notable advantages of Industry 4.0 in the context of sustainable manufacturing. The other objective of this study are to ascertain the specific tools and components associated with Industry 4.0 that have a role in promoting the progress of a sustainable ecosystem and to do a comprehensive analysis of existing literature to find out the effectiveness of technologies of Industry 4.0 in promoting environmental sustainability. This study identifies and examines 18 significant uses of Industry 4.0 that contribute to the development of a sustainable environment. This research shows that the convergence of Industry 4.0 and the sustainable development goals improves environmental sustainability by establishing ecological support that ensures superior environmental performance with a greater positive influence than previously. This paper aims to assist stakeholders and organizations in addressing current environmental concerns by implementing innovative technologies. This study is novel in that it illustrates the integration of Industry 4.0 and its technologies with sustainable development goals, resulting in a sustainable Industry 4.0 that combines environmental protection and sustainability.

Keywords Industry 4.0 · Sustainability · Environment · Technologies · Innovation

1 Introduction

Industrialization is an essential process in manufacturing. Numerous organizations that have not embraced information technology (IT) are facing significant challenges in their efforts to remain viable. In the current corporate landscape, businesses across all sectors and industries have a common perspective on the future and strive to avoid unexpected outcomes. Consequently, all industries are embracing Industry 4.0 because of its ability to deliver

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high-quality product customization. Nevertheless, despite the various advantages of Industry 4.0, there remains a significant and environmentally unsustainable use of resources, raw materials, information, and energy [1, 2]. However, there are some researchers who argue that sustainability is regarded as a supplementary issue within the perspective of fourth industrial revolution [3]. The advent of Industry 4.0 in 2011 marked a significant milestone in the manufacturing sector, facilitated by the integration of digital technology [4]. The primary objective of this initiative was to enhance the overall performance of production processes [5]. The utilization of Information Technology (IT) and digitization, facilitated by the Internet, has created an opportunity for the interchange of information and data between humans and machines. This enables the integration, interaction, and potential activation of supply chain entities, consumers, and other pertinent stakeholders within the manufacturing system [6]. The implementation of Industry 4.0 is expected to offer several benefits, including the potential for massive customization through enhanced flexibility in the production process. This would enable enterprises to manufacture personalized items while significantly decreasing the time necessary to introduce them to the market [7, 8]. Additionally, it is said that this initiative holds the potential to enhance production, minimize resource utilization, enhance quality, and optimize productivity [9, 10]. The notion of the circular economy is also advocated for by Industry 4.0 [11, 12].

This paper suggests that the principles and objectives of Industry 4.0 technologies extend beyond traditional organizational business and economic success, and will instead help to the establishment of a more sustainable society. It is crucial for practitioners to have a deep comprehension of Industry 4.0 technologies and their conceptual connections to the sustainability of society, particularly when making decisions about capital investment. The advent of Industry 4.0 signifies a significant societal and high-tech shift that has the potential to profoundly reshape the worldwide landscape [13]. The information fits in perfectly with the rest of the part, allowing for various management tasks such as buying any necessary components that may be missing and configuring specific production parameters. Simultaneously, customers are provided with regular updates regarding the current state of manufacturing [14]. Once the facility commences its operations, a greater volume of data is created. The precise results and real-world information about performance can be collected, analyzed, and incorporated into the development process. The integration and utilization of advanced technologies serve to enhance and optimize novel technological advancements and operational procedures. In the context of Industry 4.0 [15, 16]. The ability to adjust production levels in an intelligent plant is more efficient, allowing for rapid scaling up or down. As a consequence, the production plant experiences an increase in its revenues. The integration of Big data analytics and cloud computing is expected to facilitate the connectivity of IoT and Industrial IOT devices, therefore improving the experience for users and enabling highly efficient industrial processes [17]. Cloud storage is characterized by its great efficiency, extensive range of features, as well as its flexibility, up-to-dateness, and stability. The cloud platform also serves as a widely used medium for facilitating the connection of goods to companies on a global scale, making it particularly adept at managing large volumes of data created by the Internet of Things (IoT) [18].

The implementation of environmentally conscious and ecologically sustainable practices necessitates engaging in manufacturing processes that yield significant positive effects on world health. If individuals prioritize sustainability with a focus on addressing business challenges, it has the potential to provide substantial financial and environmental outcomes. Incorporating sustainable growth as a fundamental guiding principle would bring about a paradigm shift in the operational practices of firms, rather than treating it as a secondary consideration. In order to address environmental challenges pertaining to waste management, resource efficiency, carbon neutrality, and water conservation, the utilization of advanced technologies such as the use of ML and AI may be employed [19–21]. The application of Industry 4.0 in this industry has primarily prioritized production and maximizing revenues, resulting in various challenges for other aspects. For instance, the exhaustion of natural resources, adverse effects on the environment, unequal distribution of income, and unsuitable working conditions, all of which can ultimately result in an ecologically, economically, and even socially unsustainable consumption pattern.

Industry 4.0 facilitates the integration of equipment, sensors, and other devices with individuals tasked with overseeing production processes and optimizing efficiency. This is achieved through the utilization of wireless network technology and the capabilities of the Internet of Things (IoT) [22]. The utilization of these advancements facilitates operators' access to a wide range of information, thereby equipping them with the required knowledge to make informed and suitable decisions. The enhancement of connection facilitates the collection of large volumes of data and expertise by operators across various stages of the manufacturing chain. This enables them to support development efforts, identify key areas for innovation, and drive transformative changes [23, 24]. Combining sustainable manufacturing techniques with Industry 4.0 technology synergistically influences and shapes discussions surrounding production. Meanwhile, the assessment of environmental impacts and future growth has gained prominence [7, 25].

The promotion of a sustainable mindset entails the collaborative dissemination of knowledge, the cultivation of innovative thinking, and the establishment of behaviors that are both ecologically conscious and economically viable, while also prioritizing the well-being of individuals. In order to address the pressing issue of the impending climate disaster and work towards a more sustainable future, it is imperative that immediate action is taken and individual responsibility is assumed [26, 27]. The challenges pertaining to the dependability of the system's connectivity can be effectively addressed through the execution of Industry 4.0, which aims to enhance effectiveness and meet reliability requirements. The urgency around the incorporation of safety measures in the field of Information Technology (IT) has expressively increased. In the meanwhile, career readiness could be directed towards the management and oversight of cyber connections, a domain where the need for skilled personnel is anticipated to expand [28]. Anticipating the forthcoming revolution, novel forms of interaction between humans and computers are expected to arise. The integration of online platforms and computational intelligence will enhance output consistency by mitigating the impact of human error on production line tasks. This transformation has the potential to enhance the dependability of lines of products for manufacturers within the industry [29].

Numerous scholarly articles have been written on the subject of Industry 4.0. However, examining and clarifying the advantages of Industry 4.0 in the context of sustainable production is the main objective of this study. In order to conduct this investigation, pertinent research articles were reviewed and analyzed to identify the notable applicability for promoting environmental sustainability.

1.1 Significance of this research

The technologies associated with Industry 4.0 have the capacity to facilitate the connection of all relevant parties, as well as the combination of inputs and outputs to produce a useful asset for advancing long-term viability and stimulating economic expansion. Technologies associated with Industry 4.0 need to have their features analyzed in light of environmental sustainability. Companies are under increasing pressure from constituents such as legislators, investors, customers, and the news media to take environmental concerns into account and take appropriate action [30]. The manufacturing and promotion of several goods and services are profoundly affected by climate change. The outcome is characterized by a favorable triple bottom line. In the contemporary corporate landscape, it is imperative for organizations to adeptly address social, financial, and commercial objectives with a view to obtain sustainability. One of the most notable advancements in Industry 4.0 is the integration and merging of virtual and actual realms [31, 32]. The advent of Industry 4.0 has facilitated the integration of numerous innovative technologies necessary for the efficient operation of our organization. Moreover, it has fostered a burgeoning platform that will assist us in our endeavors to broaden our reach and adjust to changing circumstances. The incorporation of digital data and intellectual property plays a crucial role in the effective administration of a company's durable product information. The integration of driving producers, manufacturing, and supply chains is consolidated into a singular form of reality [33].

1.2 Major advantages of the Industry 4.0 paradigm

Industries have successfully executed their strategies belong to to the adoption of Industry 4.0 developments, hence gaining a competitive advantage over their rivals. Organizations have the opportunity to transition into the forthcoming phase of manufacturing and delivery by implementing modular and efficient automation systems that are enhanced by data-driven input. This approach enables them to exercise comprehensive control over supply and material flow. Industry 4.0 offers several benefits, such as heightened competition and achievement, expanded flexibility and pliability, and augmented profitability. The employment of Industry 4.0 has the prospective to enhance consumer service as well [34]. The technology of Smart Factory is highly intriguing and captivating. The benefits of Industry 4.0 ought to keep to be a central topic in all discussions. Robotics, machine-to-machine communication, off-the-shelf production methods, and computational aids for decision-making are all part of this category of innovations. Improvements in manufacturing efficiency and quality are made possible by Industry 4.0 developments. In alternative parlance, this has the potential to yield greater quantities at a faster rate, hence enhancing the cost-efficiency and dependability of the capital [35]. These technological advancements facilitate the democratization of data, enabling the dissemination of insights on a wider scale, and adopting and implementing the software standards of Industry 4.0. The goal of Industry 4.0 entails the establishment of networked devices that facilitate connections extending beyond the physical boundaries of production plants [36].

It is imperative to effectively utilize these technologies across the whole value chain and extend their reach into inter-organizational supply chain networks. The application of ML and AI in the analysis of instantaneous information collected across the chain of supply can lead to enriched decision-making abilities and better operational efficiency. The successful implementation of this endeavor necessitates the establishment of a robust network of collaborative partners, including start-ups and technology corporations. These entities will play a pivotal role in developing user-friendly and cost-effective technologies, thereby enabling the realization of this transformative revolution. Additionally, the academic community will engage in development and research endeavors in order to further progress technologies [37, 38]. Manufacturing processes allowed by Industry 4.0 have the capability to effectively track and monitor raw materials and the progression of work throughout several stages of production, ultimately leading to efficient and precise outbound export. By integrating robots and sensors, companies will be able to exercise comprehensive control over the material and information flow within their factories. The establishment of regulatory measures plays a critical role in ensuring consistency and productivity within the digital realm, given the rapid evolution of consumer demands and the working environment [39].

1.3 Industry 4.0 prerequisites for the establishment of environmental sustainability

It is imperative to establish a policy that enables enterprises to effectively adopt Industry 4.0. Constant retraining and improving are of utmost importance due to the impact of technological advancements and digitization, which result in the displacement of several individuals while simultaneously generating new employment opportunities. Different markets and regions have different levels of success with implementing Industry 4.0. Therefore, the implementation of a "transformative" industrial strategy might be necessary to integrate these elements with emerging digital technologies [40]. This would necessitate the acquisition of a novel set of skills that are centered on enhanced adaptability and the utilization of real-time data and operational transparency. The line setups may need to be modified based on the specific product, execution requirements, and the operator's expertise. It may be necessary to temporarily suspend the operation in order to restore the production line and provide training on an alternative process, in response to the daily demands, repairs, or necessary changes [41].

The advent of Industry 4.0 has managed to a change in production and manufacturing facilities across many continents. The impetus for reevaluating several aspects of conventional industries, including manufacturing lines, work areas, along with supply chains, stems from emerging technological advancements and the availability of extensive data reservoirs [42]. IoT has an important part in all Industry 4.0 endeavors, including the use of IIoT tools. The comprehensive ideology of Industry 4.0 encompasses several applications such as robotic integration within manufacturing facilities, sensor-based automation in greenhouse environments, and advanced systems within healthcare settings. These applications are designed to facilitate the collecting of data from a diverse variety of technologies and sensors. IoT is designed with the objective of gathering data. The utilization of applications that utilize AI/ML is essential for numerous enterprises [43, 44]. The significance of Industry 4.0 lies in its associated applications, which offer substantial benefits to a wide range of production organizations, spanning from small and medium-sized enterprises to large corporations, across various industries and organizational contexts. Companies that have adopted and integrated elements of Industry 4.0 within their organizational structures have experienced significant success [45].

1.4 Sustainable production with Industry 4.0

Sustainability in production has come a long way in the last several years, with a particular theme gaining widespread attention. The objective of sustainable manufacturing is to incorporate the core principles of sustainable growth into the manufacturing industry. The aforementioned phenomenon enhances social, environmental, and financial efficacy [46]. Industry 4.0 encompasses a comprehensive framework that integrates technological, social, and organizational elements, combining digitalization innovations, massive data sets, cyber-physical architecture, augmented and virtual reality, and the use of cloud-based computing. Sustainable manufacturing stands to benefit greatly from the ideas put out by Industry 4.0, as it has the ability to enhance productivity through the optimization of procedures, reduction of lead times, and improvement of overall company productivity. The manufacturing sector continues to face many challenges and risks [47]. The concepts of large-scale data, evaluation, as well as deep learning appear to possess an air of anonymity, and they have brought about substantial transformations in the majority of our everyday technological advancements. Certain enhancements have been implemented to enhance the regularity and efficiency of communication with technology and information [48].

In the past few years, the energy business has increasingly embraced technology, following a trend observed throughout several significant sectors. The replacement of physical papers with electronic devices that are digital is no longer solely a matter of technological progress. The subsequent step entails the transformation of business operations, communication, and collaboration methods employed by organizations in their interactions with users [49, 50]. During a similar timeframe, there has been a notable increase in the proficiency of hardware providers and companies that develop software in the creation and integration of corporate programs designed for large-scale business processes. These efforts have mostly centered on ensuring internal reliability and implementing environmentally sustainable security measures. The process of digitization presents businesses with the opportunity to develop novel business models, generate renewable energy, and devise energy supply strategies, all while benefiting from declining costs and the rapid advancement of technology [51, 52].

1.5 A few studies on Industry 4.0 for environmental sustainability and research gap

Contemporary industries are increasingly prioritizing the enhancement of their sustainability efficiency. An increasing number of regulations are being addressed, in addition to the requests made by other businesses, and occasionally, administrative management necessitates the adoption of ecologically sustainable practices [53]. Additionally, it is evident that a considerable number of employees exhibit a strong enthusiasm towards the application of environmentally sustainable industrial practices. The incorporation of Industry 4.0 technology aims to establish a platform that fosters sustainability within the environment. Numerous enterprises are presently directing their efforts towards achieving a harmonious equilibrium between sustainability objectives, including social welfare, environmental conditions, and financial gains [17]. The advent of Industry 4.0 is significantly transforming the existing landscape, challenging established norms, and offering valuable insights and support to improve sustainability and productivity, particularly within the manufacturing sector [19].

Modern technologies have succeeded in aiding organizations in achieving sustainability goals for a significant period of time, mostly by focusing on energy preservation, reduction of emissions, and optimization of value chains. In order to attain accomplishment, it is important to develop strategies that prioritize marketplace and worth chains, while also emphasizing the need for improved transparency and assessment [20]. Given the proliferation of IoT technology in contemporary times, it has become imperative for organizations to identify a viable approach to address specific pollutants or waste generated as a result of different process alternatives. Numerous corporations are presently employing a variety of digital resources in order to mitigate their energy consumption and minimize the generation of waste during production processes. In contrast, companies have traditionally assessed their success by quantifying it in terms of monetary units, such as dollars or different currencies prevalent in their respective localities [23, 54].

This study presents a comprehensive literature analysis that examines the various Industry 4.0 competences in relation to their effect on the environment as a whole. The existing body of literature pertaining to this subject matter has been deemed satisfactory in previous research, while certain gaps exist in terms of comprehensive evaluations. For example, Bai et al. analyzed the application and overall sustainability implications of Industry 4.0 technologies, considering economic, environmental, and social aspects [14]. However, our study solely concentrate on environmental sustainability. Another study by Ching et al. utilized a systematic literature review to identify 15 sustainability functions via which Industry 4.0 contributes to sustainable production [55]. Kamble et al. conducted a thorough literature assessment to identify the present trends and future prospects of Industry 4.0 [29]. Judit et al. conducted a study on the influence of Industry 4.0 on sustainability [17]. The findings suggest a detrimental correlation between the progression of the industrial process, encompassing inputs such as raw materials, energy consumption, information, and waste management, and their environmental consequences. From these above research, it can be concluded that previous studies focus mainly on the effect of Industry 4.0 overall sustainability aspects, not specifically environmental sustainability topics. To bridge this research gap, our current study completely focuses on the specific impacts of Industry 4.0 on the development of a sustainable environment. This study provides a synthesis of many publications published in reputable academic journals, with the aim of acquiring novel insights within a technical framework. This discussion briefly covers several sorts of research, including fundamental, practical, logical, quantitative, qualitative, and other methodologies.

1.6 Objectives of this research and research question

The Industry 4.0 paradigm is characterized by its significant disruptive potential, with its overarching objectives centered on facilitating organizations in attaining the necessary conditions for success. The prevalent strategic objectives for the employment of Industry 4.0 innovations encompass enhancing operational efficiency, enhancing relations with consumers, streamlining product creation through automation, and connecting production and supply chain processes. While it is widely acknowledged that the impact of Industry 4.0 is predictable to be extensive and pervasive, there exists a prevailing belief among people that this phenomenon is still in the process of development. This paper addresses multiple research aims aimed at addressing the issues posed by Industry 4.0 in the pursuit of establishing environmental sustainability. This study's general goals (research questions) are outlined below:

RQ1: To investigate substantial Industry 4.0 benefits for sustainable production.
RQ2: To examine of Industry 4.0 operations in the context of sustainable environment.
RQ3: To determine Industry 4.0 components and instruments that contribute to sustainable environment.
RQ4: To recognize and evaluate Industry 4.0 applications that contribute to a sustainable environment.
RQ5: To analyze significant advancements via Industry 4.0 in order to establish environmental sustainability.

2 Research methodology

This literature evaluation is conducted by extensively reviewing several scholarly articles, authoritative blogs, and relevant publications pertaining to the subjects of Industry 4.0, environmental sustainability environmental concerns, and other interconnected areas. In order to identify appropriate sources, we conducted a systematic literature review using bibliometric analysis, also known as SLRBA. To gain a comprehensive understanding of the topic, supported by evidence, do an extensive literature review utilizing bibliometric analysis. It aids scholars in staying updated on current research trends, visualizing collaborations, tracking productivity and impact, and identifying research deficiencies. A bibliometric analysis is a method that uses quantitative metrics such as citation numbers, co-authorship connections, and publication trends to assess the productivity and impact of research. This is different from a systematic literature review, which follows a specific search approach and inclusion/exclusion criteria to thoroughly and methodically evaluate all available information on a particular topic. The integration of bibliometric analysis with systematic review techniques enhances the credibility and reliability of decision-making processes by providing a stronger evidence base. This technique ensures that the review exclusively utilizes trustworthy sources with explicitly defined procedures, hence yielding conclusions of superior quality and relevance. A comprehensive methodology such as the SLRBA is crucial for this study as it aims to provide valuable insights that firms can utilize to enhance their decision-making and strategic planning. SCOPUS was selected as the starting point for the SLRBA due to its international representation of peer-reviewed journals, books, and conferences, which makes it one of the most comprehensive collections of citations and controlled abstracts. SCOPUS is well-known as an academic database that helps in identifying relevant sources. In addition, it utilizes an autonomous content filtering and advisory board to do comprehensive assessments and reassessments of material, ensuring that only data of the highest caliber is included in the index.

In order to identify suitable sources for investigation, we utilized the SCOPUS database. The process commenced with the phrase "Industry 4.0," yielding a grand total of 3765 outcomes. Subsequently, the inclusion of the specific keyword "Environmental Sustainability" resulted in the exclusion of 207 publications from the final results. The research domain is emerging and progressive, and conducting observable and tool-based study wouldn't have accurately reflected the future trajectory. The main aim of doing an analysis based on a review of the literature is to enhance understanding of the study issues under investigation. Additionally, we have endeavored to clarify how the study related to these breakthroughs presents novel approaches for assessing previous studies. The process of analyzing, criticizing, and synthesizing relevant literature on a certain issue facilitates the development of novel frameworks and viewpoints in an extensive way.

3 Impact of Industry 4.0 in environmental sustainability

3.1 Different Industry 4.0 features helps to the development of a sustainable environment

Figure 1 depicts the intricate network of components comprising the Industry 4.0, which aims to foster a sustainable global environment. Energy, materials, resources from nature, waste products, and pollution are among the most important Industry 4.0 sustainability factors. Subcategories of these factors include potentially dangerous level, depletion of ozone layer, and greenhouse influences in the emissions and waste part; waste rate, the technique used, and smart processes in the materials section; and the utility of water, land and capacity for recycling in the resources part. Sustainable environmental development gains momentum when these factors are properly followed up on [56–58]. A well-functioning society effectively harnesses its human, ecological, and economic assets to satisfy current societal requirements and safeguard sufficient resources for generations to come. The initiation of Industry 4.0 has ushered in substantial advancements, transforming several operational aspects within factories and industrial facilities by integrating intelligent machines and advanced technological devices. This occurrence prompts us to contemplate the significance and function of individuals within the professional setting. Additive manufacturing has served as a catalyst for substantial advancements over an extended period [59, 60]. Innovations have been present for an extended duration, with their practical applications frequently confined to the realm of prototype. A great deal of new technology has emerged in the last couple of decades and its practical implementation, extending its reach beyond the realms of design and engineering to encompass the domain of small and medium-scale production. Manufacturers have expressed a clear anticipation for the proliferation of open-source technology and solutions within the global manufacturing industry, as the IIoT proceeds to expand its reach [61, 62].

Technologies of Industry 4.0 assist to develop a smarter manufacturing system while cutting down on waste, labor, and resources. The health care and medical industries, for example, cannot function without the use of plastic packaging. Robots and flexible components from Industry 4.0 have helped create polymers fabrication procedures that reduce their water footprint and the effluent they generate during production [34, 63]. Augmented reality technology has the capability to effectively explore and select the most direct route to transfer a component located in a different sector of the industry. Additionally, this measure would enhance employees' efficiency and facilitate compliance with intricate processes. In order to establish a society that is sustainable, it is imperative to adequately acknowledge and take into account the diverse range of individual pursuits. The space provides a conducive environment and ensures the safety of many cultures and perspectives, wherein each industry is granted representation in the process of making choices [64, 65].

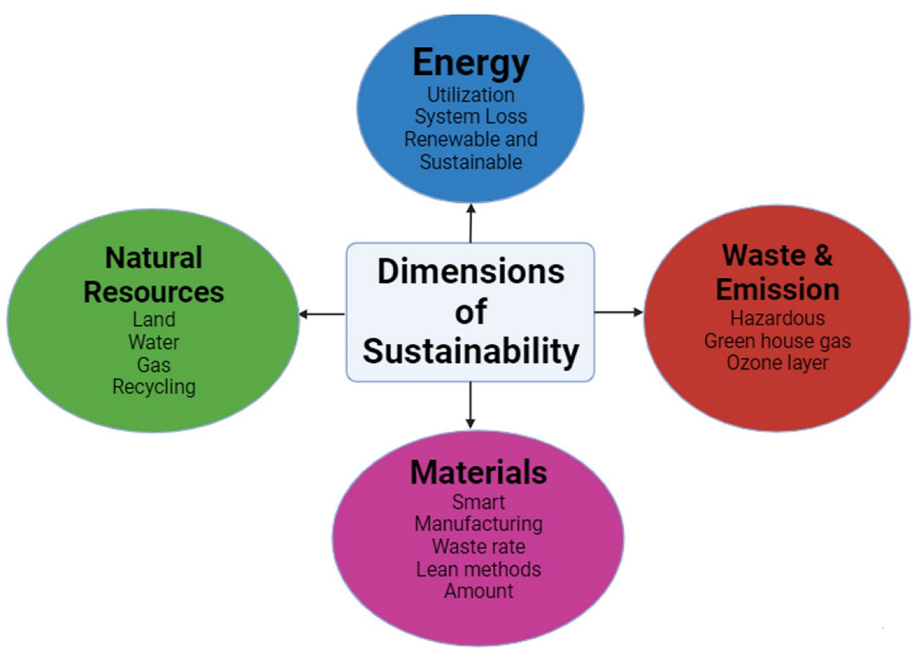

Fig. 1 Establishing sustainable environment via Industry 4.0 application

3.2 The role of Industry 4.0 in promoting environmental sustainability

The environmental sustainability, resilience, and long-term concepts that drive Industry 4.0's socio-economic growth are its defining characteristics. The implementation of this approach spans a diverse range of applications, with the aim of fostering environmental sustainability. From a technical standpoint, it can be seen that contemporary online businesses strive to prioritize environmental sustainability in their operations, aiming to create a positive impact [66]. At this very moment, we are faced with a plethora of critical problems, some of which are the escalating temperatures of our environment, excessive utilization of non-renewable energy sources, the decline of biodiversity, severe natural disasters, extensive deforestation, substantial releases of greenhouse gases such as CO_2, and diminished quality of the air and water. The integration of Industry 4.0 technology is required for the business to get advantages from environmental sustainability [67, 68]. Industry 4.0 has the capability to illustrate the economic justification, formulate suitable safety frameworks, and provide real-world uses. A device administrator with strong support may offer opportunities for gaining expertise in the field of confidential wireless connections. The individual who possesses the necessary skills and, most importantly, maintains trustworthy connections with the specific technology provider in issue may be the most suitable candidate. Technology suppliers provide valuable knowledge in integrating many sectors into Industry 4.0 production scenarios, whereas device integrators are responsible for implementing transformational initiatives [69, 70].

Proficient understanding of traditional cable infrastructures and seamless incorporation of wireless solutions in technology with no disrupting ongoing operations may be accessed through suitable technological collaborators [71]. Businesses must take into account the activities occurring on their workshop level in order to establish a structure that facilitates the creation and verification of simulations, as well as the execution of floor operations. This platform should effectively transform large sets of data into actionable insights, thereby promoting innovation and enhancing the effectiveness of operations [72, 73]. The concept of a linked factory and an IIoT interconnected plant involves the collaboration of various equipment inside a production facility. This collaboration is facilitated via the utilization of data, IoT technology, and automation, which enable the monitoring and control of all features of the production development. The growth of streamlined and protective components has enhanced our portfolio of IIoT scenarios, therefore benefiting our clients' online activities [74]. Technologies within the framework of Industry 4.0 must identify the absence of potential hazards associated with technological change, risks pertaining to cyber infrastructure, costly capital expenditures, and other related challenges. Leaders should use prudence in addressing the challenges they may encounter and the subsequent implications for long-term competitiveness [75, 76].

The relevance of technical progress in potentially protecting the environment was highlighted by the COVID-19 pandemic. During the pandemic period, there has been a significant decline in road and air traffic, resulting in a notable decline in emissions of greenhouse gases. This decrease can be attributed to the increased number of individuals staying at home and relying on online resources for daily activities such as travel, shopping, and entertainment. The constraints presented opportunities for the process of digitalization, leading to the emergence of new firms that prioritize a contemporary environment devoid of physical contact in operations and transactions [77–80]. Now is the opportune moment to revolutionize the electronic medium rather than simply contemplating its existence. Numerous countries have developed smartphone applications that establish connections across essential health systems and provide guidance to consumers on optimal practices, self-evaluation, hazards, and other recommendations pertaining to COVID-19. Frequently, these applications notify individuals of a favorable outcome, enabling them to engage in self-isolation or contact the relevant healthcare practitioner in the case of experiencing symptoms [81–83].

To enhance the elucidation of the virus of COVID-19, its transmission, and patient response to treatment, the utilization of AI was implemented to analyze databases, pathological tracks, and information about patients. Prominent information technology companies, insurance firms, financial service providers, and educational institutions are actively engaged in an unparalleled telecommuting experiment. Virtual offices provide several benefits for workers, including time and resource savings, reduced energy consumption due to decreased transportation, and the capacity for achieving a balance between job responsibilities and sustainable growth and development. The bonuses for employees include the dropping of overhead costs and the improvement of operational efficiency [78, 84]. Various websites and applications facilitate the process of live streaming. The COVID-19 pandemic is anticipated to bring about significant transformations in the grocery store and online purchasing sectors, leading to a renaissance in these businesses [85–87].

3.3 Industry 4.0 tools and components to create a sustainable environment

The key aspects of Industry 4.0's toolkit which are responsible for the preservation of the environment encompass several components like the IoT, cloud computing based on data, distinct principles of Industry 4.0, and considerations connected to products and processes as shown in Fig. 2. The wide array of instruments that are linked to the Industry 4.0 paradigm, which are crucial in fostering the development of an environment that is sustainable [88–90]. By implementing appropriate strategies and utilizing Industry 4.0 technologies, it is possible to accomplish sustainable environmental growth. The following issues are expounded upon: interoperability, real-time systems, life cycle evaluation, big data as well as information in real time, intelligent manufacturing, digitalization, the use of sensors, and others [91, 92]. The current corporate landscape will undergo transformation as a result of emerging technology advancements, including AI, IoT, huge amounts of data, and related innovations. Within the framework of Industry 4.0, AI is an essential component to consider, facilitating cognitive abilities in machines, including thinking, learning, and decision-making capabilities. Throughout the course of human history, individuals have consistently endeavored to enhance their physical and cognitive capacities. These toolings offer dependable tools for cutting-edge research [93, 94].

The IoT is a notable technical achievement wherein computers are capable of engaging in interactions with one another. IoT is likely to facilitate the relocation of manufacturing to smart urban and rural areas, as well as the transformation of automobiles and residences into smart entities. Substantial analysis of data is identified as another crucial component within the framework of Industry 4.0. The fundamental objective of this framework is to gather feedback and data from consumers, enabling producers to provide products and services tailored to their needs. The service is sufficiently prompt, resulting in the conservation of both time and resources [96, 97]. Global economy operations have been profoundly impacted by the introduction of Industry 4.0, leading to substantial changes in its foundational principles. Engineers employ the outcomes of extensive data analytics derived from the framework in order to facilitate decision-making processes. This body of knowledge emphasizes the need of implementing modifications and implementing actions aimed at mitigating the occurrence of unplanned machine downtimes. The exploitation of Big Data Analysis in the context of predictive maintenance has been seen to significantly reduce reaction time. The application of Big Data Analysis by manufacturers extends to the automated supply control. This implies a reduction in the level of human interaction necessary inside an industrial plant [98–100]. In actuality, the trajectory of technology advancements has predominantly exhibited a progressive pattern, with historical revolutions typically unfolding throughout protracted periods spanning a number of decades. To clarify, this is the initial instance in which contemporary cyber infrastructure is being integrated into several industrial sectors [101, 102].

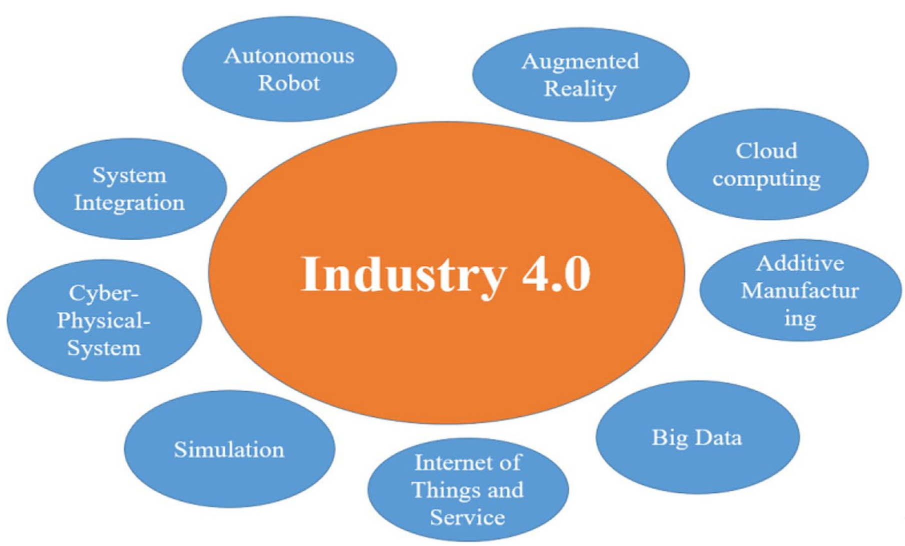

Fig. 2 Key technologies of Industry 4.0 framework [95]

3.4 The processes of Industry 4.0 aim to attain a sustainable environment

Integration of processes and production of sustainable outcomes are the fundamental stages within Industry 4.0's process flow domains. The process starts by implementing intelligent and digital aspects, which subsequently facilitates the establishment of an efficient and enduring culture. The use of intelligent advancements in procedures and processes is crucial for the creation of environmentally sustainable products. The concept of integration pertains to the interface between humans and machines, as well as their interconnectedness with instantaneous control and virtualization within the environment of intelligent manufacturing plants [103–105]. In the framework of sustainable manufacturing, the mitigation of harmful emissions is achieved by using of alternative energy sources and the implementation of environmentally friendly lighting, machinery, and equipment. This frequently amplifies the purchasing experience of several individuals [106]. The advent of Industry 4.0 has led to enhanced customer service and improved quality of life through the utilization of sophisticated robotics, which contribute to increased industrial efficiency and the provision of superior gadgets for consumers. Additive manufacturing facilitates the customization of materials, enabling the creation of novel structures and shapes while minimizing the requirement for additional equipment and reducing waste generation [107, 108]. The ideology of Industry 4.0 emphasizes the establishment of a zero-waste policy within an internet-based circular economy, aiming to minimize material consumption and adopt an innovative approach to product development and distribution chains. In contemporary settings, sensors are employed to detect and measure the moisture, temperature, and other pertinent factors within the spray chamber. Consequently, any alterations in these variables prompt corresponding deviations from the ideal environmental configuration, thereby affecting the efficiency of operation of the machines [109].

4 Prominent advancements facilitated by Industry 4.0 in the pursuit of environmental sustainability

The "Internet of Service" (IoS) and the "Internet of Things" (IoT) are such components of cyber-physical systems that are involved in the "Industry 4.0" definition of modern manufacturing. In previous times, the computer was utilized for manufacturing purposes. However, the current focus lies on the integration of operations, collaboration, and making decisions in a smart way, eliminating the need for human involvement [110]. Industry 4.0 will transform architecture, manufacturing, and services. Manufacturers and wholesalers have used this method for years to reduce uncertainty and improve efficiency. Lean values promote organizational adaptability, efficiency, and intelligence. Industry 4.0 technologies create lean supply chains and networking. Digitizing equipment has modernized lean processes and introduced new technology. Continuous organizational excellence can only be achieved this way. [111, 112]. When lean practices are combined with Industry 4.0, high-performance maintenance systems can be set up that can efficiently exchange data with other connected devices. Professionals' decision-making in today's competitive markets relies heavily on their ability to gather and analyze information from a variety of sources [54, 113]. Through careful study, the device can anticipate failures, alter its configuration, and respond to changes. Predictive management analyses massive data sets using real-time monitoring. This method uses regression analysis to warn and notify. Mining has the key to maintaining global economic prosperity. However, the necessity for environmentally sustainable and secure alternatives to natural resources raises worries about global warming and carbon emissions [114].

Technological advancements like the capture and storage of carbon have the ability to significantly mitigate the ecological impacts associated with mining activities. This involves the extraction of CO_2 from submerged storage locations and its subsequent sequestration in the atmosphere, effectively immobilizing it for extended periods of time, hence minimizing its release throughout the mining process [115, 116]. After mining, mines are closed and regenerated to maintain a stable environment. Researchers synthesised a polymer to boost plant growth in heavy metal-polluted soils. The industrial sector is becoming digital, automated, and complex, reliant on computers and advanced technology. Industry 4.0 describes the trend towards increasing interconnection, automated procedures, and artificial intelligence in numerous businesses [117].

Technology integration is crucial to factory preparedness because it combines continuous manufacturing with adaptive installation stability. We can quickly adapt to consumer demands due to our increased flexibility.

Compared to conventional conveyor systems, it requires less investment. Natural resource-based businesses confront problems from resource shortages, environmental degradation, and climate change. Thus, they prioritize ecologically responsible options that promote financial growth while minimizing climatic damage.[118]. Industry 4.0 generates a beneficial impact by employing organized methodologies, encompassing goods, procedures, and system-level innovative approaches, to foster sustainable value creation. The achievement of this objective necessitates a continual flow of closed-loop elements throughout the production process, facilitated by effective waste disposal systems, the use of lean manufacturing principles, and the utilization of technologies tailored to support sustainable manufacturing methods [119]. Sustainable industrial technology protects the environment and ensures methodological cleanliness. Industrialization has tarnished various ecosystems. Lean manufacturing is a complex strategy used to equalise industrial growth across socioeconomic structures. This strategy helps achieve sustainable production by applying 4R: Reduce, Reuse, Recycle, and Recover in resource management. [120]. The major advancements related to Industry 4.0 that contribute to the establishment of an environment that is sustainable are outlined below:

4.1 The utilization of Industry 4.0 to decrease energy usage

Intelligent cities strive to enhance their standard of life and minimize energy usage through the utilization of Internet of Things (IoT) technologies. Business entities will collaborate to guarantee the active participation of urban populations in the ongoing energy revolution. The utility companies anticipate the formulation of a strategic outlook pertaining to innovative residential areas and advanced technological solutions, including intelligent parking systems [121, 122]. Manufacturers estimate and build statements that show the potential for energy savings during production, increased yield and waste, and lower transportation costs due to fewer customer claims. Industry 4.0 innovations and technologies help people grasp their goals from the start of the innovation process. These technologies also aid decision-making in subsequent phases. Based on technological advances, efficiency gains, and other important aspects, this phenomenon's predicted worth is regularly calculated using previous innovation and research experiences [123, 124].

4.2 Intelligent manufacturing with Industry 4.0 technology

Intelligent manufacturing refers to the integration and real-time operation of information technology (IT) systems. Modern technology is capable of detecting and recording tags through the automated use of electric fields. The use of chips has been observed, and advancements in their designs have significantly enhanced their dependability, rendering them suitable for utilization in production-oriented contexts [125]. Numerous sectors presently employ microchips as a means to oversee their stock, mitigate unforeseen periods of inactivity, and enhance asset utilization. The idea behind Industry 4.0 is the coordinated effort of people, procedures, and technology. Hence, it is imperative to integrate them at a pace that won't result in worker confusion [126]. Start by doing a readiness assessment to spot potential areas for low-cost, high-impact Industry 4.0 innovations. Drones can be used to gather information at various points in a project, which can then be used to inform different types of scenarios, tools, computerized reports, examinations, and more in-depth decision-making and outcome analysis [127, 128].

4.3 Industry 4.0's commitment to information transparency

The interconnectivity and openness of information facilitate decision-making for operators within and outside production facilities. The capacity to integrate local as well as international intelligence concurrently has a tendency to augment decision-making capabilities and boost overall efficiency. The application of big data analysis is employed to identify significant correlations, trends, patterns, and consumer preferences within vast datasets, hence facilitating commercial advancement in the realm of computer technology. Big data analysis used within the framework of Industry 4.0 offers far-reaching consequences, particularly in the area of smart manufacturing. In this regards, the analysis of sensor data from production machines enables the proactive identification of maintenance and repair requirements [129].

Companies encounter manufacturing efficiency and leverage self-service solutions to get real-time data. They also employ proactive maintenance optimization and utilize manufacturing technology. Big analytical firms leverage substantial quantities of customer data to improve strategic decision-making through the comprehension of patterns as well as the identification of trends. Using cloud computing, the system collects massive volumes of data from cutting-edge sensors and IIoT platforms in order to identify trends that enhance the effectiveness of supply chain management [130]. Covert output variables can be found using big data analysis. Producers use selected data analysis to identify bottleneck sources. This encourages producers to increase productivity while reducing expenses and waste. Big data analytics aims to improve supply chain efficiency, pricing optimization, defect prediction, product development, and smart factory building. The consolidation of massive manufacturing facility data can be streamlined with self-service choices engineering evaluation. For decision-makers, the self-service platform allows real-time data analysis, pattern recognition, mistake tracking, and visualization.

4.4 Water-specific aspects of Industry 4.0

New possibilities for better asset management are presented by Industry 4.0, encompassing functionalities like real-time remote surveillance, smart water examination, and alarm-triggered preventative maintenance. By using dependable surveillance methods, this study proposes strategies to boost the efficiency of climate response, strengthen community engagement and communication networks, and guarantee the sustained provision of water resources to both rural and urban regions [131]. These capabilities enable the water sector to effectively meet growing needs, efficiently manage infrastructure and resources, and optimize operational expenses while providing improved and expedited service to consumers. The industry sector is currently undergoing a change process similar to that experienced by retail and financial organizations over the past many years [28].

4.5 Industry 4.0 to cut down air pollution

Solar panels and other forms of renewable energy infrastructure may be connected to the reliable power grid. Technologies based on software for an intelligent grid are used at these establishments. Emissions and the quality of the air in cities may be drastically improved by using automated methods [132]. No haze is being produced, and the air is improving. The roadways can have better traffic management and reduced congestion as a result. Smart cities will drastically cut their energy use, garbage production, and greenhouse gas emissions. To achieve national sustainable goals, we require zero-waste systems that encourage maximum reuse, recycling, and revitalization across all industries [133]. Digitization enables a single market. Owners, landlords, and affiliated websites enable house, car, motorbike, and appliance sharing. Resources must be pooled to reduce waste and digital transformation costs. Green technology and a new digital transformation are happening simultaneously. However, considering both together was rare. Only in the past decade has exponential progress been tied to cutting-edge technology and environmental responsibility. Every organization needs vast digital operations. Thus, cumulative digitization has great promise for sustainable goals [134].

4.6 Industry 4.0's role in connecting supply chains

Supply chain integration is not limited to the manufacturing sector alone. The whole chain of supply, including the suppliers, may be connected laterally. The process industry won't thrive without Industry 4.0, especially the manufacturing sector, but it also generates social uncertainties that are comparable to those in which processors were involved at the same time. The new fourth industrial revolution is more of a controlled system than an unbridled upheaval [135]. Computerized future world prediction has significant implications for both production and upkeep. Sensors play a vital part in embracing Industry 4.0, instead of merely an important smart supply chain. Sensor data must be properly analyzed and consistently of high quality [136, 137]. Predictive maintenance is only one example of how forward, downstream, and simultaneous systems may benefit from Industry 4.0 technology. Without the right sensors, all more advanced devices are flying blind, making poor judgments based on unreliable data. Effective and quick sensor calibration is crucial for accurate data collection, which the maintenance crew may find surprising. Automate and improve the factory floor with the help of intelligent machines; this technology transformation will have an impact on both businesses. By allowing manufacturers to demonstrate their wares and procedures to customers in a simulated environment, virtual reality is revolutionizing manufacturing processes and implementation lines in the factory. It allows for the resolution of issues and the delivery of high-quality item to customers. This information, collected by various Internet-of-Things devices, may be used to predict future occurrences [138].

4.7 Operational control using Industry 4.0

Embedded technology from Industry 4.0, such as intelligent instruments, infrared representation, and commercial recording devices, allows the manufacturer to collect data on assembling and regulate activities. The result was improved productivity, accountability, and competitiveness across the board [139]. Smart engineering aiding cutting-edge technologies like IoT, AI, augmented and virtual reality, and ML: that's Industry 4.0. In order to improve their security, rivalry, and dependability, businesses are implementing improvements today that will allow our clients and collaborators to bring this truth closer to the forefront [140]. Interoperability is especially important in the design of smart manufacturing facilities since it guarantees that inputs will produce the expected outputs. In certain cases, this is due to the unreliability of external or internal organizations. Manufacturers and enterprises have a track record of meeting or exceeding customer expectations, according to available evidence [141]. Businesses in the manufacturing sector would benefit from learning more about decentralized innovation processes and making greater use of cloud analytics. For this, we'll need to employ cutting-edge strategies like crowdsourcing to get usable information. Technology, electronic devices and airplanes have all advanced thanks to technological breakthroughs. AI, robots, additive manufacturing, sensors, and other technologies are currently propelling us toward the Industry 4.0 era. This new wave of change is a big motivator. There will likely be fundamental shifts in the way commerce and economics function [142].

4.8 Some applications of Industry 4.0 to establish environmental sustainability

In Industry 4.0, digital technology is integrated into the manufacturing process alongside physical labor. In order to increase productivity, streamline operations, and speed up development, businesses may take use of machine learning as well as data processing in real time. With the help of Industry 4.0 breakthroughs and technology, manufacturing may have entered a new sustainable era. By increasing efficiency, performance, adaptability, and dependability, the use of digital technology helps firms succeed financially and endure for the long haul. Companies make investments in intelligent production because of the promise of increased output volumes and efficiencies along with reduced operating, capital, and administrative expenses [143, 144].

Industry 4.0 allows us to learn both the qualitative and quantitative benefits of intelligent manufacturing. The operations of these supplementary providers consist of component packing and shipment of goods and shortened delivery times and prices [145]. To alleviate most problems and provide value to plant operations, the underlying network infrastructure must be as solid, reliable, and future-proof as feasible. The potential of 5G technology lies in its ability to provide a unified infrastructure for high-volume, high-security, and high-volume industrial automation use cases. Advanced cellular IoT and cyber-physical networks made possible by 5G are preparing the way for the next wave of industrialization [146, 147]. Improved industrial output and a deeper comprehension of the climate impact are both conceivable due to the Internet of Things. The fourth industrial revolution emerges at the perfect the midst of the most vital era for action on climate change. The implementation of IoT would be greatly simplified with the advent of 5 G networking [148]. On the manufacturing floor, one exciting technological concept that we are implementing is the employment of remote specialists. Using VR, a user may communicate with a local service expert and receive assistance in real-time [149, 150]. Here, we have compiled a comprehensive list of 18 specific applications of Industry 4.0 that contribute to the development of environmental sustainability. While Industry 4.0 has a wide range of applications, the authors of this study have identified and determined 18 specific applications after examining relevant literature. This 18 is a random number, it could be more or less.

Applications	Brief description
Enhanced productivity	Industry 4.0 aims to boost output, competitiveness, and ROI. The rewards are immediate and can start a cycle of investment, return, and more investment depending on success. Competition boosts financial outcomes, which can be used to expand capacity and output. Energy efficiency is crucial to Industry 4.0. This helps forward-thinking companies maximise their resources and services. In an increasingly complex and fragmented market, numerous energy sources must be integrated [101, 151–153]

Applications	Brief description
Optimization of production	To an outsider, a cloud-based computing network seems to function as a unified whole. Manufacturing optimization, risk forecasting, and reduced downtime can all benefit from this information. Each component, sensor, actuator, gadget, artificial intelligence, and human may share and receive information more effectively and freely when systems are interoperable. Industrial machines and other computers are increasingly being operated via cloud services. Big data and analytics are terms used to describe the massive and ever-changing data sets made possible by advances in machine learning technologies [154–157]
Smart, sustainable plants	Industry 4.0 will become standard in the smart industrial unit of the future as more companies adopt greener manufacturing practices. Production and manufacturing underpin the global economy. Businesses now can use connected manufacturing gear, AI-powered power grids, and other IIoT devices. We can promote sustainable development and use by using Industry 4.0 technologies. The global organization's responsible resource management is based on circular economy and climate consciousness [158–161]
Digital data with a favorable impact on the environment	This encompasses the range of services and goods offered by our organization, as well as the utilization of technology for digital communication and information to effectively address and reduce the favorable environmental effects caused by various industries. Various instances in the process of production have been found, examined, and implemented in industrial settings to substantiate and measure the beneficial effects of smart manufacturing through the utilization of digital technology [162–165]
Friendly to the environment	Higher levels of automation improve worker safety and efficiency. Wireless remote controls and haptic feedback over 5G networks enable heavy machine control. This idea improves public safety and environmental sustainability. Implementing IoT technology has improved mining safety and activities and enabled various new use cases. Automating ventilation systems, monitoring workers and vehicles in real time, and using remote-controlled equipment are examples [166, 167]
Waste Minimization	The automotive industry enthusiastically adopted lean. Zero waste is the goal of lean production. Lean thinking can save producers money on packing, supplies, and power. The action performed in relation to the effects of climate change gives a chance to improve public perception and economic growth through green branding and sustainable practices. There appears to be a correlation between the concentration of cheap sensors, collaboration, and analysis of big data, all of which contribute to a productive manufacturing system. These advances teach manufacturers and distributors how to optimise operations for cost savings and better customer service [168–170]
Waste material recycling and reusing	Some examples of strategies that encourage sustainable manufacturing processes include recycling to extend and reuse raw resources, using domestic waste products, and creating interconnected marketplaces for differentiating by-products. The efficiency of many manufacturing facilities has increased as a result of new emphasis on ecological production methods. Gains in manufacturing resource efficiency via the utilization of immense amounts of data generated by robots define the future of "Industry 4.0." Due to an increase in available options, this also benefits health care [16, 171, 172]
Lower carbon emissions and controlling pollution	Factories in several industries have made strides toward lessening their plastic and rubber, carbon, and contamination of water effects. Industry 4.0 technologies including robots, renewable energy, data collecting and forecasting, the Internet of Things, and digitalization are crucial to this. Electricity, trash, and traditional energy sources are not required for production. Institutions dedicated to research and development make use of the aforementioned technological advancements. Future studies will focus on topics including solar energy use, security of energy, and construction that is lightweight [173, 174]

Applications	Brief description
Consideration of climate change	Industry will profit from these climate change and sustainability initiatives and tools. The exponential roadmap improves collaboration between scholars, corporate executives, and social activists. World economies are about to deteriorate. Due to digital technology's widespread availability, new firm structures and exciting consumer opportunities have emerged. Innovative business models that increase security, inclusivity, affordability, and sustainable development for all parties may also affect civilisations' sustainability [175–178]
Sustainable construction	Industry 4.0 can make buildings sustainable from construction to maintenance. BIM software helps architects create greener buildings. Use digital technology to add eco-friendly microorganisms that repair structures to commercial and industrial buildings. Industry 4.0 provides green building plans and methods. HVAC systems automatically optimise energy efficiency after installation. Sensors and Internet of Things devices may alert environmental control systems to switch off lights and HVAC when users leave a facility [179–181]
Improving skills and making automation more flexible:	Training is needed for Industry 4.0 jobs. Academic and practical education improves company solutions and builds a ready workforce. Technological breakthroughs in the past century have changed business and industry. Tech-heavy Industry 4.0 merges systems, computers, and products. Flexible automation relies on robotics for soldering, plasma cutting, assembling, and finishing. Any provider can benefit from robots. Properly deployed robot systems improve quality management, workplace health, job flow, efficiency, and employee pleasure [182–184]
Increased long-term advantages	These developments suggest a complete approach to technical advances, manufacturing, and sustainability effect analysis to maximise intelligent production's sustainability benefits. Many technologies and criteria are used to evaluate and categorise manufacturing processes, including 5G commercial wireless connection, IoT, AI, and VR/AR. Innovative ideas improved business processes, environmental responsibility, and collaboration between producers, distributors, and customers [185–187]
Enhancing the efficiency of markets	Through thorough and cost-effective waste management, sustainable manufacturing connections and complexity overlap areas, locations, and categorised attributes of diverse processes, improving market efficiency and modelling. Modern organisations use renewable energy for energy and modern technologies for production, distribution, and supply chain activities. Organisations also use innovative methods and technology to improve energy management, decrease costs, and expedite processes [188–191]
Management of products and services	Industry 4.0 is done by integrating measurement devices and a comprehensive architecture for industrial businesses' information and automation, especially in power and service management. Increased capacity to gather, transport, and store energy supply, utilisation, production, and transformation data. Advanced AI approaches may now identify and analyse variable styles of interest across numerous sectors due to increased data availability and computer resources [192–195]
Management of all industrial activities	Industries automating their operations should not disregard the importance of current data. All company data is instantly available from any computer with cloud computing. Sensors and cameras may improve engineer efficiency by offering insight. Production engineers might offer maintenance workers the product's entire assembly instructions to demonstrate shop floor concerns. Industrial processes and supply chains can now incorporate 3D printing and nanotechnology, making manufacturing more flexible and resource-efficient [196–198]
Innovation for ecological betterment	Industry 4.0 includes cutting-edge green automation and commercial collaboration. Machine-human communication has improved automated industrial processes, lowering waste and increasing efficiency. An IoT network comprising actuators, sensors, and computers may share data. Virtual twins mimic real-world items and systems. Digital twins enable future planning, data collection, device monitoring, and more. Advanced processing, networking, mechanical processes, and physical and natural surroundings are common in cyber-physical arrangements [199–201]

Applications	Brief description
Fast assessment and correction of a wide range of problems	Most industries have cut new product production and consumer delivery times. Big savings for the company and industry. This level of detail allows new item advice, routine maintenance, and error detection and elimination. No standard regulation governs alternative approaches and implementations, so organisations cannot handle these issues alone. Sustainability consultancy services help companies of all sizes and sectors meet their environmental performance goals using Industry 4.0 technologies, professional software, and industry-specific information. These concepts could change factory floor small-scale production [202–204]
Execute all the essential tasks	Machine learning (ML) is an area of artificial intelligence (AI) that develops algorithms and models that can analyse and interpret data without scripting. One major research and development project identified educational, strategic, subsidy, working group, and advanced research opportunities for SMEs. This sector prioritises data protection processes to prevent exploitation of personal and business data [205–207]

5 Discussion and insights of the study

Firstly, it is important to note that the environment offers a limited and insufficient supply of natural resources. Hence, it is crucial to emphasize that sustainability holds immense significance, not just for businesses but also for the society and the aspects of economic progress. If these resources are not conserved and protected, corporations would soon run out of raw materials for manufacturing. An optimal scenario for environmental sustainability occurs when natural resources have the potential to replenish themselves and may be utilized without negatively impacting the production life cycle. The concept at hand cannot be accurately measured using a specific scale, but rather by observing changes in sustainability.

Environmental sustainability may be measured by progressing towards a distant objective from the ideal sustainability point, in order to attain both sustainable production and consumption. Considering this, we assessed the sustainability effects by evaluating if there was a progression or regression towards a sustainable condition that incorporates and promotes the United Nations sustainable development goals (SDGs). In this instance, we attempted to employ pertinent factors that would provide explicit significance to our situations. Consequently, our objective was not to assess or quantify indicators, but rather to employ a methodical methodology and an exploratory viewpoint. This offers a clear comprehension of the subject matter, avoiding any vague or intricate methods for ascertaining how to guarantee the long-term viability of the ecosystem.

By incorporating quality into a company's overarching approach for using technology, Industry 4.0 offers a unique competitive edge. Industry 4.0 is already being implemented in many contexts throughout the world, and it is transforming several sectors, from production to customer service. The time is here for businesses to adopt Industry 4.0. Using the tools made available by the Fourth Industrial Revolution (I4.0), designers may create digital blueprints based on their own unique body of knowledge. The dangers of mistakes in manufacturing, labeling, and packing are plain to see. Being vigilant and conducting rigorous testing and controls appropriate for Industry 4.0 technologies is crucial. Making a greater quantity of the same product by taking benefit of economies of size is one of the primary advantages of the initial production adjustments. Mechanical producers absolutely must accomplish this delivery. Industry 4.0 has the potential to deliver all of the necessary answers. Digitally developed integrated workflows in intelligent manufacturing facilities simplify and adapt the design and production of any goods beyond imagination.

Industry 4.0, which is the latest revolution in industry, can boost green production. Smart factories create massive volumes of data, requiring data analysts, machine learning specialists, and Big Data experts to analyze, optimize, and maintain the production. This sees a possibility and trains us for a new assignment utilizing new technology. Almost anything may be concluded from the data. Without digitization, business models and manufacturing costs were hard to measure and understand. Resource shortages, electricity demand, and energy limitations affected industry operations. Nevertheless, the incorporation of robots, AI, and ML has facilitated the process of data acquisition pertaining to these concerns inside factories. Consequently, this advancement enables factories to strive towards the development of a facility capable of effectively managing limitations associated with power, raw materials, and energy. This would result in a substantial reduction in manufacturing expenses, therefore aiding enterprises in enhancing their competitiveness and stability. The phenomenon in question has been in existence for a number of years and is projected to experience further expansion in the upcoming months, hence fostering increased levels of innovation and enhanced quality. The current era of industrial transformation presents an opportunity for us to actively capitalize on its potential and construct a more significant, purpose-oriented, and environmentally sustainable milieu. The fundamental aim of the present structure is to provide a thorough set of rules on how to apply Industry 4.0 technology in a way that supports and promotes sustainability. Predominantly, the investigation aimed to analyze an organization's decision-making process in determining the prioritization of sustainability problems.

6 Implications of this study

While this research does not specifically aim to measure the quantitative impact, it is important to note that the environmental impact is greatly influenced by the use of biophysical resources. In order to fully capitalize on the advantages of Industry 4.0, it is essential to establish and enforce effective policies that safeguard and preserve the environment and its ecosystems from the adverse effects of Industry 4.0, particularly in relation to energy transition and policy development for the use of different instruments. All parties should be concerned about this. Develop policies that align with Industry 4.0 and its technology, while also promoting energy efficiency in production, transportation, and consumption, in order to ensure a sustainable future.

The notion of environmental effect may be conveyed through factors such as population, trash, and technology. Evidence of beneficial effects in subjective terms has been discovered through the use of this method, which is associated with the third concept. To estimate the quantitative environmental impact of Industry 4.0 technology, it is necessary to use specific approaches such as material intensity, life cycle analysis, and energy calculations. In order to implement such a framework, it is necessary to provide a certain context and time period. However, this is not within the scope of our research. Policymakers would gain valuable insights by conducting scenario-based research, enabling them to anticipate the effects resulting from the transformation of Industry 4.0 on production systems. Nevertheless, the development of Industry 4.0 is ongoing and it is encountering several obstacles that require regular examination in order to prevent any adverse effects on environmental sustainability.

Each day, the population and consumption of resources are growing, but we fail to utilize technology (namely Industry 4.0) that might effectively manage the situation and promote sustainability. Considerable emphasis has been placed on prioritizing profit generation at the expense of neglecting environmental preservation and social considerations. Sustainability cannot be attained by addressing a single component, but rather encompasses three fundamental dimensions. Industry 4.0 is a crucial tool for overcoming obstacles, but if not properly integrated, it might have disastrous consequences. Based on future projections, it is evident that resources will inevitably become depleted due to the escalating pace of daily consumption and production. Proper management of recycling, reusing, and reducing may be quite beneficial. Hence, it is very recommended that all parties involved implement these 3Rs. Furthermore, the use of technology, namely Industry 4.0, is strongly promoted. Additional investigation may be conducted on the 3Rs using a rigorous scientific approach. Furthermore, governments should allocate additional funding for research and development, providing policymakers with a competitive edge in anticipating and mitigating the most severe outcomes. Another obstacle arises from the lack of collaboration among stakeholders, necessitating enhanced consultation through training sessions, seminars, and workshops to foster awareness.

7 Conclusions

The main objectives of this paper was to explore the utilization of Industry 4.0 in the field of environmental sustainability from existing literature. Firstly, the brief introduction of Industry 4.0 and environmental sustainability has been discussed. This research study investigates the influence of Industry 4.0 technologies on the promotion of environmental sustainability in the manufacturing sector and other associated industries. The adoption of Industry 4.0 technologies and the complex linkages enabled by current technology are anticipated to have a beneficial impact on the environment. In the era of Industry 4.0, the integration of communication and information technology has led to a close relationship between industrial production and technology. This has resulted in improved scalability, competitiveness, and the acquisition of knowledge. Industry 4.0 refers to a collection of principles, recommendations, and technical innovations that support the development and functioning of both new and existing industrial facilities. This framework enables customers to choose from a range of production models, while taking use of adaptable robotics, information systems, and communication technologies that may be customized to suit different levels of output.

This study aims to analyze the significant benefits of Industry 4.0 in the context of sustainable manufacturing. Moreover, the goal of this study is to determine the precise tools and components linked to Industry 4.0 that contribute to the advancement of a sustainable ecosystem. The intent of this study is to conduct a thorough examination of current literature in order to determine the efficacy of Industry 4.0 technologies in advancing environmental sustainability. Moreover, it provides a thorough analysis of the possible uses of Industry 4.0 in addressing environmental issues. This report identifies and analyses 18 important applications of Industry 4.0 that contribute to the advancement of a sustainable environment. Thus, this offers a more thorough understanding of the manufacturing environment, distribution networks, delivery systems, and market results. Overall, the implementation of Industry 4.0 technology seems to have environmental sustainability characteristics. This is because it allows for the manufacture of commodities with improved efficiency, resulting in a decrease in resource consumption.

One of the most important aspects of sustainable energy management that may be improved with the support of Industry 4.0 technology is digital automation. The mineral extraction, oil, and gas industries rely on IoT technologies like robotics and data analysis to maintain operational productivity at required levels. The positive effects of digitalization on many different industries are increasingly seen in their respective intelligent supply networks. IoT sensors integrated with drone are employed in facility and line inspections, opening up new avenues for promoting environmental sustainability. Petroleum, water, gas, and consumption of energy information are all up-to-date on smart grid meters. Temperature, humidity, and vibration variations may also be detected by IoT systems, allowing for the prevention of system failure and the enhancement of human safety. Input from Internet of Things (IoT) equipment linked to a company's physical twin can be used in the digital twin's tracking of key success indicators. The goal is to use the information in machine learning systems, notify operators of potential issues, calculate potential expenses, and offer ecologically responsible remedies. Using digitalized information as a sustainable operating platform, the cloud can process a potentially endless amount of industrial data. In order to teach new employees how to create complex algorithms, new technology can replace human data entry in a computerized database. The manufacturer needs to be able to adapt quickly to fluctuating consumer demand, emerging product trends, a shortage of qualified workers, and other upcoming challenges.

7.1 Limitations and future research directions

This study is only focused on the impact of Industry 4.0 on environmental sustainability. More study is required on sustainability in the social and economic spheres in addition to the environment because of the topic's complexity and significance for future generations. Furthermore, the utilization of PRISMA (Preferred Reporting Items for Systematic reviews and Meta-Analyses) might enhance the robustness of this research. Besides, the presence of intricacy in both natural and technological environments invariably influences the extent of comprehension. If we overlook some crucial elements pertaining to the system under investigation, it might potentially compromise the efficacy of our decision-making process. In addition, it is crucial to analyze the structural, functional, and qualitative factors.

In Industry 5.0, humans and machines work together more. Industry 5.0 continues the cyber-physical connection that began with Industry 4.0, altering living, thinking, and interacting. The next technology revolution must define human–robot cooperation and how we work together. As automated processes, artificial intelligence for machines, and robots help people and take over distribution, manufacturing, and operations, human–machine collaboration will expand. Due to rapid change, workers, governments, legislators, and regulators struggle. Worker participation is a hallmark of Industry 5.0. Manufacturers must use technologies that enable client customization, product development, and after-sales assistance to meet rising demand.

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

Declarations

Competing interests 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.

References

1. Dubey R, Gunasekaran A, Childe SJ, Blome C, Papadopoulos T. Big data and predictive analytics and manufacturing performance: integrating institutional theory, resource-based view and big data culture. Br J Manag. 2019;30(2):341–61.
2. Bokrantz J, Skoogh A, Berlin C, Wuest T, Stahre J. Smart Maintenance: a research agenda for industrial maintenance management. Int J Prod Econ. 2020;224:107547.
3. Ghobakhloo M, Fathi M, Iranmanesh M, Maroufkhani P, Morales ME. Industry 4.0 ten years on: a bibliometric and systematic review of concepts, sustainability value drivers, and success determinants. J Clean Prod. 2021;302:127052.
4. Oztemel E, Gursev S. A taxonomy of Industry 4.0 and related technologies. Ind. 2020;40:45.
5. Faller C, Feldmüller D. Industry 4.0 learning factory for regional SMEs. Procedia Cirp. 2015;32:88–91.
6. Pereira AC, Romero F. A review of the meanings and the implications of the Industry 4.0 concept. Procedia Manuf. 2017;13:1206–14.
7. Brozzi R, Forti D, Rauch E, Matt DT. The advantages of Industry 4.0 applications for sustainability: results from a sample of manufacturing companies. Sustainability. 2020;12(9):3647.
8. Ersoy Y. The advantages and barries in implementing of Industry 4.0 and key features of Industry 4.0. J Int Sci Res. 2022;7(3):207–14.
9. Davies R. Industry 4.0: digitalisation for productivity and growth. 2015. https://policycommons.net/artifacts/1335939/industry-40/1942749/. Accessed 30 Oct 2023.
10. Rüßmann M, et al. Industry 4.0: the future of productivity and growth in manufacturing industries. Boston Consult Group. 2015;9(1):54–89.
11. Rajput S, Singh SP. Connecting circular economy and Industry 4.0. Int J Inf Manag. 2019;49:98–113.
12 Tavera Romero CA, Castro DF, Ortiz JH, Khalaf OI, Vargas MA. Synergy between circular economy and Industry 4.0: a literature review. Sustainability. 2021;13(8):4331.
13. Bhuiyan A, Ali M, Zulkifli N, Kumarasamy M. Industry 4.0: challenges, opportunities, and strategic solutions for Bangladesh. Int J Bus Manag Future. 2020;4:41–56. https://doi.org/10.46281/ijbmf.v4i2.832.
14. Bai C, Dallasega P, Orzes G, Sarkis J. Industry 4.0 technologies assessment: a sustainability perspective. Int J Prod Econ. 2020;229:107776.
15. Furstenau LB, et al. Link between sustainability and Industry 4.0: trends, challenges and new perspectives. IEEE Access. 2020;8:140079–96.
16 Bányai T, Tamás P, Illés B, Stankevičiūtė Ž, Bányai Á. Optimization of municipal waste collection routing: impact of Industry 4.0 technologies on environmental awareness and sustainability. Int J Environ Res Public Health. 2019;16(4):634.
17 Oláh J, Aburumman N, Popp J, Khan MA, Haddad H, Kitukutha N. Impact of Industry 4.0 on environmental sustainability. Sustainability. 2020;12(11):4674.
18. Franciosi C, Iung B, Miranda S, Riemma S. Maintenance for sustainability in the Industry 4.0 context: a scoping literature review. IFAC-Pap. 2018;51(11):903–8.
19. Tiwari K, Khan MS. Sustainability accounting and reporting in the Industry 4.0. J Clean Prod. 2020;258:120783.
20. Javaid M, Haleem A. Industry 4.0 applications in medical field: a brief review. Curr Med Res Pract. 2019;9(3):102–9.
21. Garcia-Muiña FE, et al. Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design. Soc Sci. 2019;8(8):241.
22. Chaim O, Muschard B, Cazarini E, Rozenfeld H. Insertion of sustainability performance indicators in an Industry 4.0 virtual learning environment. Procedia Manuf. 2018;21:446–53.
23 Maresova P, et al. Consequences of Industry 4.0 in business and economics. Economies. 2018;6(3):46.
24. Burritt R, Christ K. Industry 4.0 and environmental accounting: a new revolution? Asian J Sustain Soc Responsib. 2016;1(1):23–38. https://doi.org/10.1186/s41180-016-0007-y.
25 Salah B, Abidi MH, Mian SH, Krid M, Alkhalefah H, Abdo A. Virtual reality-based engineering education to enhance manufacturing sustainability in Industry 4.0. Sustainability. 2019;11(5):1477.
26. Luthra S, Mangla SK. Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. Process Saf Environ Prot. 2018;117:168–79.
27. Sharma M, Kamble S, Mani V, Sehrawat R, Belhadi A, Sharma V. Industry 4.0 adoption for sustainability in multi-tier manufacturing supply chain in emerging economies. J Clean Prod. 2021;281: 125013.
28 Ejsmont K, Gladysz B, Kluczek A. Impact of Industry 4.0 on sustainability—bibliometric literature review. Sustainability. 2020;12(14):5650.
29. Kamble SS, Gunasekaran A, Gawankar SA. Sustainable Industry 4.0 framework: a systematic literature review identifying the current trends and future perspectives. Process Saf Environ Prot. 2018;117:408–25.
30. García-Muiña FE, Medina-Salgado MS, Ferrari AM, Cucchi M. Sustainability transition in Industry 4.0 and smart manufacturing with the triple-layered business model canvas. Sustainability. 2020;12(6):2364.
31. Ghafoorpoor Yazdi P, Azizi A, Hashemipour M. An empirical investigation of the relationship between overall equipment efficiency (OEE) and manufacturing sustainability in Industry 4.0 with time study approach. Sustainability. 2018;10(9):3031.
32. Kerin M, Pham DT. A review of emerging Industry 4.0 technologies in remanufacturing. J Clean Prod. 2019;237:117805.
33 Haleem A, Javaid M. Additive manufacturing applications in Industry 4.0: a review. J Ind Integr Manag. 2019;04(04):1930001. https://doi.org/10.1142/S2424862219300011.
34 Müller JM, Kiel D, Voigt K-I. What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. Sustainability. 2018;10(1):247.

35. Jamwal A, Agrawal R, Sharma M, Kumar V, Kumar S. Developing A sustainability framework for Industry 4.0. Procedia CIRP. 2021;98:430–5.
36 Miśkiewicz R, Wolniak R. Practical application of the Industry 4.0 concept in a steel company. Sustainability. 2020;12(14):5776.
37. Moshood TD, Adeleke AQ, Nawanir G, Ajibike WA, Shittu RA. Emerging challenges and sustainability of Industry 4.0 era in the Malaysian construction industry. Emerg Chall Sustain Ind. 2020;4:1627–34.
38 Vrchota J, Pech M, Rolinek L, Bednář J. Sustainability outcomes of green processes in relation to Industry 4.0 in manufacturing: systematic review. Sustainability. 2020;12(15):5968.
39. Moktadir MA, Ali SM, Kusi-Sarpong S, Shaikh MAA. Assessing challenges for implementing Industry 4.0: implications for process safety and environmental protection. Process Saf Environ Prot. 2018;117:730–41.
40. Beier G, Ullrich A, Niehoff S, Reißig M, Habich M. Industry 4.0: how it is defined from a sociotechnical perspective and how much sustainability it includes—a literature review. J Clean Prod. 2020;259:120856.
41. Varela L, Araújo A, Ávila P, Castro H, Putnik G. Evaluation of the relation between lean manufacturing, Industry 4.0, and sustainability. Sustainability. 2019;11(5):1439.
42. Ivanov D. New drivers for supply chain structural dynamics and resilience: sustainability, Industry 4.0, self-adaptation. In: Structural dynamics and resilience in supply chain risk management, in International Series in Operations Research & Management Science, vol. 265. Cham: Springer International Publishing; 2018. p. 293–313. https://doi.org/10.1007/978-3-319-69305-7_10.
43. Ammar M, Haleem A, Javaid M, Walia R, Bahl S. Improving material quality management and manufacturing organizations system through Industry 4.0 technologies. Mater Today Proc. 2021;45:5089–96.
44. Bhagawati MT, Manavalan E, Jayakrishna K, Venkumar P. Identifying key success factors of sustainability in supply chain management for Industry 4.0 using DEMATEL method. In: Vasudevan H, Kottur VKN, Raina AA, editors. Proceedings of international conference on intelligent manufacturing and automation. Lecture Notes in Mechanical Engineering. Springer Singapore: Singapore; 2019. p. 583–91. https://doi.org/10.1007/978-981-13-2490-1_54.
45. Birkel HS, Veile JW, Müller JM, Hartmann E, Voigt K-I. Development of a risk framework for Industry 4.0 in the context of sustainability for established manufacturers. Sustainability. 2019;11(2):384.
46 Saniuk S, Grabowska S, Gajdzik B. Social expectations and market changes in the context of developing the Industry 4.0 concept. Sustainability. 2020;12(4):1362.
47. Dossou P-E. Impact of sustainability on the supply chain 4.0 performance. Procedia Manuf. 2018;17:452–9.
48. Chong S, Pan G-T, Chin J, Show PL, Yang TCK, Huang C-M. Integration of 3D printing and Industry 4.0 into engineering teaching. Sustainability. 2018;10(11):3960.
49. Dalenogare LS, Benitez GB, Ayala NF, Frank AG. The expected contribution of Industry 4.0 technologies for industrial performance. Int J Prod Econ. 2018;204:383–94. https://doi.org/10.1016/j.ijpe.2018.08.019.
50. Stock T, Seliger G. Opportunities of sustainable manufacturing in Industry 4.0. Procedia CIRP. 2016;40:536–41.
51. Mendoza-del Villar L, Oliva-Lopez E, Luis-Pineda O, Benešová A, Tupa J, Garza-Reyes JA. Fostering economic growth, social inclusion & sustainability in Industry 4.0: a systemic approach. Procedia Manuf. 2020;51:1755–62.
52. Junior JAG, Busso CM, Gobbo SCO, Carreão H. Making the links among environmental protection, process safety, and Industry 4.0. Process Saf Environ Prot. 2018;117:372–82.
53. Ghobakhloo M. Industry 4.0, digitization, and opportunities for sustainability. J Clean Prod. 2020;252:119869.
54. Blunck E, Werthmann H. Industry 4.0—an opportunity to realize sustainable manufacturing and its potential for a circular economy. In: DIEM: Dubrovnik International Economic Meeting, Sveučilište u Dubrovniku. 2017; p. 644–66. https://hrcak.srce.hr/clanak/276314. Accessed 5 Nov 2023.
55. Ching NT, Ghobakhloo M, Iranmanesh M, Maroufkhani P, Asadi S. Industry 4.0 applications for sustainable manufacturing: a systematic literature review and a roadmap to sustainable development. J Clean Prod. 2022;334:130133. https://doi.org/10.1016/j.jclepro.2021.130133.
56. Stachová K, Papula J, Stacho Z, Kohnová L. External partnerships in employee education and development as the key to facing Industry 4.0 challenges. Sustainability. 2019;11(2):345.
57. Sajid S, Haleem A, Bahl S, Javaid M, Goyal T, Mittal M. Data science applications for predictive maintenance and materials science in context to Industry 4.0. Mater Today Proc. 2021;45:4898–905.
58. Abbasi A, Kamal MM. Adopting Industry 4.0 technologies in citizens' electronic-engagement considering sustainability development. In: Themistocleous M, Papadaki M, editors. Information systems, vol. 381. Lecture Notes in Business Information Processing. Cham: Springer International Publishing; 2020. p. 304–13. https://doi.org/10.1007/978-3-030-44322-1_23.
59 Lin KC, Shyu JZ, Ding K. A cross-strait comparison of innovation policy under Industry 4.0 and sustainability development transition. Sustainability. 2017;9(5):786.
60 Prause M. Challenges of Industry 4.0 technology adoption for SMEs: the case of Japan. Sustainability. 2019;11(20):5807.
61. Garcia-Muiña FE, González-Sánchez R, Ferrari AM, Settembre-Blundo D. The paradigms of Industry 4.0 and circular economy as enabling drivers for the competitiveness of businesses and territories: the case of an Italian ceramic tiles manufacturing company. Soc Sci. 2018;7(12):255.
62. Manavalan E, Jayakrishna K. A review of Internet of Things (IoT) embedded sustainable supply chain for Industry 4.0 requirements. Comput Ind Eng. 2019;127:925–53.
63. Morrar R, Arman H, Mousa S. The fourth industrial revolution (Industry 4.0): a social innovation perspective. Technol Innov Manag Rev. 2017;7(11):12–20.
64. Stock T, Obenaus M, Kunz S, Kohl H. Industry 4.0 as enabler for a sustainable development: a qualitative assessment of its ecological and social potential. Process Saf Environ Prot. 2018;118:254–67.
65. Ashima R, Haleem A, Bahl S, Javaid M, Mahla SK, Singh S. Automation and manufacturing of smart materials in Additive Manufacturing technologies using Internet of Things towards the adoption of Industry 4.0. Mater Today Proc. 2021;45:5081–8.
66. Micieta B, Binasova V, Lieskovsky R, Krajcovic M, Dulina L. Product segmentation and sustainability in customized assembly with respect to the basic elements of Industry 4.0. Sustainability. 2019;11(21):6057.

67. Mian SH, Salah B, Ameen W, Moiduddin K, Alkhalefah H. Adapting universities for sustainability education in Industry 4.0: Channel of challenges and opportunities. Sustainability. 2020;12(15):6100.
68. Vuksanović Herceg I, Kuč V, Mijušković VM, Herceg T. Challenges and driving forces for Industry 4.0 implementation. Sustainability. 2020;12(10):4208.
69. Sima V, Gheorghe IG, Subić J, Nancu D. Influences of the Industry 4.0 revolution on the human capital development and consumer behavior: a systematic review. Sustainability. 2020;12(10):4035.
70. Shrouf F, Ordieres J, Miragliotta G. Smart factories in Industry 4.0: a review of the concept and of energy management approached in production based on the Internet of Things paradigm. In: 2014 IEEE international conference on industrial engineering and engineering management, IEEE; 2014. p. 697–701. https://ieeexplore.ieee.org/abstract/document/7058728/. Accessed 5 Nov 2023.
71 Kiel D, Müller JM, Arnold C, Voigt K-I. Sustainable industrial value creation: benefits and challenges of Industry 4.0. Int J Innov Manag. 2017;21(08):1740015. https://doi.org/10.1142/S1363919617400151.
72. de Man JC, Strandhagen JO. An Industry 4.0 research agenda for sustainable business models. Procedia Cirp. 2017;63:721–6.
73. Bagheri B, Yang S, Kao H-A, Lee J. Cyber-physical systems architecture for self-aware machines in Industry 4.0 environment. IFAC-Pap. 2015;48(3):1622–7.
74. Garg D, Mustaqueem OA, Kumar R. Industry 4.0 technologies and ethical sustainability. In: Advances in Industrial and Production Engineering: Select Proceedings of FLAME 2020. Springer; 2021. p. 189–99. https://doi.org/10.1007/978-981-33-4320-7_17.
75. Ding B. Pharma Industry 4.0: literature review and research opportunities in sustainable pharmaceutical supply chains. Process Saf Environ Prot. 2018;119:115–30.
76. Saucedo-Martínez JA, Pérez-Lara M, Marmolejo-Saucedo JA, Salais-Fierro TE, Vasant P. Industry 4.0 framework for management and operations: a review. J Ambient Intell Hum Comput. 2018;9(3):789–801. https://doi.org/10.1007/s12652-017-0533-1.
77. Ilmi Z, Darma DC, Azis M. Independence in learning, education management, and Industry 4.0: habitat Indonesia during COVID-19. J Anthropol Sport Phys Educ. 2020;4(4):63–6.
78. Javaid M, Haleem A, Vaishya R, Bahl S, Suman R, Vaish A. Industry 4.0 technologies and their applications in fighting COVID-19 pandemic. Diabetes Metab Syndr Clin Res Rev. 2020;14(4):419–22.
79. Kumar MS, Raut RD, Narwane VS, Narkhede BE. Applications of Industry 4.0 to overcome the COVID-19 operational challenges. Diabetes Metab Syndr Clin Res Rev. 2020;14(5):1283–9.
80. Narayanamurthy G, Tortorella G. Impact of COVID-19 outbreak on employee performance–moderating role of Industry 4.0 base technologies. Int J Prod Econ. 2021;234:108075.
81. Haleem A, Javaid M. Medical 4.0 and its role in healthcare during COVID-19 pandemic: a review. J Ind Integr Manag. 2020;05(04):531–45. https://doi.org/10.1142/S2424862220300045.
82 Sarfraz Z, Sarfraz A, Iftikar HM, Akhund R. Is COVID-19 pushing us to the fifth industrial revolution (society 5.0)? Pak J Med Sci. 2021;37(2):591.
83. Acioli C, Scavarda A, Reis A. Applying Industry 4.0 technologies in the COVID–19 sustainable chains. Int J Product Perform Manag. 2021;70(5):988–1016.
84. Abdel-Basset M, Chang V, Nabeeh NA. An intelligent framework using disruptive technologies for COVID-19 analysis. Technol Forecast Soc Change. 2021;163:120431.
85 Sharma R, Shishodia A, Kamble S, Gunasekaran A, Belhadi A. Agriculture supply chain risks and COVID-19: mitigation strategies and implications for the practitioners. Int J Logist Res Appl. 2020. https://doi.org/10.1080/13675567.2020.1830049.
86 Cyfert S, Glabiszewski W, Zastempowski M. Impact of management tools supporting Industry 4.0 on the importance of csr during covid-19. generation z. Energies. 2021;14(6):1642.
87. Vaishya R, Haleem A, Vaish A, Javaid M. Emerging technologies to combat the COVID-19 pandemic. J Clin Exp Hepatol. 2020;10(4):409–11.
88. Haleem A, Vaishya R, Javaid M, Khan IH. Artificial Intelligence (AI) applications in orthopaedics: an innovative technology to embrace. J Clin Orthop Trauma. 2020;11(Suppl 1):S80.
89 de Sousa Jabbour ABL, Jabbour CJC, Foropon C, Godinho Filho M. When titans meet—can Industry 4.0 revolutionise the environmentally-sustainable manufacturing wave? The role of critical success factors. Technol Forecast Soc Change. 2018;132:18–25.
90 Ahmad S, Miskon S, Alabdan R, Tlili I. Towards sustainable textile and apparel industry: exploring the role of business intelligence systems in the era of Industry 4.0. Sustainability. 2020;12(7):2632.
91. Yadav G, Luthra S, Jakhar SK, Mangla SK, Rai DP. A framework to overcome sustainable supply chain challenges through solution measures of Industry 4.0 and circular economy: an automotive case. J Clean Prod. 2020;254:120112.
92. Khanzode AG, Sarma PRS, Mangla SK, Yuan H. Modeling the Industry 4.0 adoption for sustainable production in Micro, Small & Medium Enterprises. J Clean Prod. 2021;279:123489.
93. Paravizo E, Chaim OC, Braatz D, Muschard B, Rozenfeld H. Exploring gamification to support manufacturing education on Industry 4.0 as an enabler for innovation and sustainability. Procedia Manuf. 2018;21:438–45.
94 Pham TT, et al. Industry 4.0 to accelerate the circular economy: a case study of electric scooter sharing. Sustainability. 2019;11(23):6661.
95. Shabur MdA, Rahman KA, Siddiki MdR. Evaluating the difficulties and potential responses to implement Industry 4.0 in Bangladesh's steel sector. J Eng Appl Sci. 2023;70(1):158. https://doi.org/10.1186/s44147-023-00336-z.
96 Tirabeni L, De Bernardi P, Forliano C, Franco M. How can organisations and business models lead to a more sustainable society? A framework from a systematic review of the Industry 4.0. Sustainability. 2019;11(22):6363.
97. Tseng M-L, Tan RR, Chiu AS, Chien C-F, Kuo TC. Circular economy meets Industry 4.0: can big data drive industrial symbiosis? Resour Conserv Recycl. 2018;131:146–7.
98 Scavarda A, Daú G, Scavarda LF, Goyannes Gusmão Caiado R. An analysis of the corporate social responsibility and the Industry 4.0 with focus on the youth generation: a sustainable human resource management framework. Sustainability. 2019;11(18):5130.
99. Haleem A, Javaid M, Khan IH. Current status and applications of Artificial Intelligence (AI) in medical field: an overview. Curr Med Res Pract. 2019;9(6):231–7.
100. Xu LD, Xu EL, Li L. Industry 4.0: state of the art and future trends. Int J Prod Res. 2018;56(8):2941–62.
101. Tsai W-H, Lu Y-H. A framework of production planning and control with carbon tax under Industry 4.0. Sustainability. 2018;10(9):3221.

102 Fritzsche K, Niehoff S, Beier G. Industry 4.0 and climate change—exploring the science-policy gap. Sustainability. 2018;10(12):4511.
103 Kagermann H. Change through digitization—value creation in the age of Industry 4.0. In: Albach H, Meffert H, Pinkwart A, Reichwald R, editors. Management of permanent change. Wiesbaden: Springer Fachmedien Wiesbaden; 2015. p. 23–45. https://doi.org/10.1007/978-3-658-05014-6_2.
104. Büchi G, Cugno M, Castagnoli R. Smart factory performance and Industry 4.0. Technol Forecast Soc Change. 2020;150:119790.
105. Machado CG, Winroth MP, Ribeiro Da Silva EHD. Sustainable manufacturing in Industry 4.0: an emerging research agenda. Int J Prod Res. 2020;58(5):1462–84. https://doi.org/10.1080/00207543.2019.1652777.
106. Prause G, Atari S. On sustainable production networks for Industry 4.0. Entrep Sustain Issues. 2017;4(4):421–31.
107. Belaud J-P, Prioux N, Vialle C, Sablayrolles C. Big data for agri-food 4.0: application to sustainability management for by-products supply chain. Comput Ind. 2019;111:41–50.
108. Godina R, Ribeiro I, Matos F, Ferreira BT, Carvalho H, Peças P. Impact assessment of additive manufacturing on sustainable business models in Industry 4.0 context. Sustainability. 2020;12(17):7066.
109. Yin Y, Stecke KE, Li D. The evolution of production systems from Industry 2.0 through Industry 4.0. Int J Prod Res. 2018;56(1–2):848–61. https://doi.org/10.1080/00207543.2017.1403664.
110. Azizi SM, Soroush A, Khatony A. The relationship between social networking addiction and academic performance in Iranian students of medical sciences: a cross-sectional study. BMC Psychol. 2019;7(1):1–8.
111. Meissner H, Ilsen R, Aurich JC. Analysis of control architectures in the context of Industry 4.0. Procedia Cirp. 2017;62:165–9.
112. Huang Z, Yu H, Peng Z, Feng Y. Planning community energy system in the Industry 4.0 era: achievements, challenges and a potential solution. Renew Sustain Energy Rev. 2017;78:710–21.
113. Liao Y, Deschamps F, Loures EDFR, Ramos LFP. Past, present and future of Industry 4.0—a systematic literature review and research agenda proposal. Int J Prod Res. 2017;55(12):3609–29. https://doi.org/10.1080/00207543.2017.1308576.
114. Liu Y, Zhu Q, Seuring S. New technologies in operations and supply chains: implications for sustainability. Int J Prod Econ. 2020;229:107889.
115. Ma J, et al. Carbon capture and storage: history and the road ahead. Engineering. 2022;14:33–43.
116. Gomes MG, et al. Economic, environmental and social gains of the implementation of artificial intelligence at dam operations toward Industry 4.0 principles. Sustainability. 2020;12(9):3604.
117. Galati F, Bigliardi B. Industry 4.0: Emerging themes and future research avenues using a text mining approach. Comput Ind. 2019;109:100–13.
118 de Sousa Jabbour ABL, Jabbour CJC, Godinho Filho M, Roubaud D. Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations. Ann Oper Res. 2018;270(1–2):273–86. https://doi.org/10.1007/s10479-018-2772-8.
119. Gu F, Guo J, Hall P, Gu X. An integrated architecture for implementing extended producer responsibility in the context of Industry 4.0. Int J Prod Res. 2019;57(5):1458–77. https://doi.org/10.1080/00207543.2018.1489161.
120. Yu KH, Zhang Y, Li D, Montenegro-Marin CE, Kumar PM. Environmental planning based on reduce, reuse, recycle and recover using artificial intelligence. Environ Impact Assess Rev. 2021;86:106492.
121. Buer S-V, Strandhagen JO, Chan FTS. The link between Industry 4.0 and lean manufacturing: mapping current research and establishing a research agenda. Int J Prod Res. 2018;56(8):2924–40. https://doi.org/10.1080/00207543.2018.1442945.
122. Nunes ML, Pereira AC, Alves AC. Smart products development approaches for Industry 4.0. Procedia Manuf. 2017;13:1215–22.
123. Choi T, Kumar S, Yue X, Chan H. Disruptive technologies and operations management in the Industry 4.0 era and beyond. Prod Oper Manag. 2022;31(1):9–31. https://doi.org/10.1111/poms.13622.
124. Bibby L, Dehe B. Defining and assessing Industry 4.0 maturity levels—case of the defence sector. Prod Plan Control. 2018;29(12):1030–43. https://doi.org/10.1080/09537287.2018.1503355.
125 Nagy J, Oláh J, Erdei E, Máté D, Popp J. The role and impact of Industry 4.0 and the internet of things on the business strategy of the value chain—the case of Hungary. Sustainability. 2018;10(10):3491.
126. Fatorachian H, Kazemi H. A critical investigation of Industry 4.0 in manufacturing: theoretical operationalisation framework. Prod Plan Control. 2018;29(8):633–44. https://doi.org/10.1080/09537287.2018.1424960.
127 Zambon I, Cecchini M, Egidi G, Saporito MG, Colantoni A. Revolution 4.0: industry vs. agriculture in a future development for SMEs. Processes. 2019;7(1):36.
128. Tortorella GL, Fettermann D. Implementation of Industry 4.0 and lean production in Brazilian manufacturing companies. Int J Prod Res. 2018;56(8):2975–87. https://doi.org/10.1080/00207543.2017.1391420.
129. Badri A, Boudreau-Trudel B, Souissi AS. Occupational health and safety in the Industry 4.0 era: a cause for major concern? Saf Sci. 2018;109:403–11.
130. Ciffolilli A, Muscio A. Industry 4.0: national and regional comparative advantages in key enabling technologies. Eur Plan Stud. 2018;26(12):2323–43. https://doi.org/10.1080/09654313.2018.1529145.
131. Chauhan A, Jakhar SK, Chauhan C. The interplay of circular economy with Industry 4.0 enabled smart city drivers of healthcare waste disposal. J Clean Prod. 2021;279:123854.
132. Xu LD, Duan L. Big data for cyber physical systems in Industry 4.0: a survey. Enterp Inf Syst. 2019;13(2):148–69. https://doi.org/10.1080/17517575.2018.1442934.
133 Rossi J, Bianchini A, Guarnieri P. Circular economy model enhanced by intelligent assets from Industry 4.0: the proposition of an innovative tool to analyze case studies. Sustainability. 2020;12(17):7147.
134. Machado CG, Winroth M, Carlsson D, Almström P, Centerholt V, Hallin M. Industry 4.0 readiness in manufacturing companies: challenges and enablers towards increased digitalization. Procedia Cirp. 2019;81:1113–8.
135. Carvalho N, Chaim O, Cazarini E, Gerolamo M. Manufacturing in the fourth industrial revolution: a positive prospect in sustainable manufacturing. Procedia Manuf. 2018;21:671–8.
136. Hecklau F, Galeitzke M, Flachs S, Kohl H. Holistic approach for human resource management in Industry 4.0. Procedia Cirp. 2016;54:1–6.
137. Oesterreich TD, Teuteberg F. Understanding the implications of digitisation and automation in the context of Industry 4.0: a triangulation approach and elements of a research agenda for the construction industry. Comput Ind. 2016;83:121–39.

138. Okano MT. IOT and Industry 4.0: the industrial new revolution. In: International Conference on Management and Information Systems; 2017. p. 26. https://www.researchgate.net/profile/Marcelo-Okano-2/publication/319881057_IOT_and_Industry_40_The_Industrial_New_Revolution/links/59c018a5aca272aff2e20639/IOT-and-Industry-40-The-Industrial-New-Revolution.pdf. Accessed 17 Nov 2023.
139. Lu Y. Industry 4.0: a survey on technologies, applications and open research issues. J Ind Inf Integr. 2017;6:1–10.
140. Leso V, Fontana L, Iavicoli I. The occupational health and safety dimension of Industry 4.0. Med Lav. 2018;109(5):327.
141. Kanoğlu A, Yazıcıoğlu D, Özçevik Ö. SIMURG: a performance-based and sustainability-oriented integration model using relational database architecture to increase global competitiveness of Turkish Construction Industry in Industry 4.0 Era. In: 5th International Project and Construction Management Conference (IPCMC2018); 2018. p. 16–8.
142. Wagner T, Herrmann C, Thiede S. Industry 4.0 impacts on lean production systems. Procedia Cirp. 2017;63:125–31.
143. Tortorella G, Miorando R, Caiado R, Nascimento D, Portioli Staudacher A. The mediating effect of employees' involvement on the relationship between Industry 4.0 and operational performance improvement. Total Qual Manag Bus Excell. 2021;32(1–2):119–33. https://doi.org/10.1080/14783363.2018.1532789.
144. Sony M. Industry 4.0 and lean management: a proposed integration model and research propositions. Prod Manuf Res. 2018;6(1):416–32. https://doi.org/10.1080/21693277.2018.1540949.
145. Marques M, Agostinho C, Zacharewicz G, Jardim-Gonçalves R. Decentralized decision support for intelligent manufacturing in Industry 4.0. J Ambient Intell Smart Environ. 2017;9(3):299–313.
146. Çınar ZM, Abdussalam Nuhu A, Zeeshan Q, Korhan O, Asmael M, Safaei B. Machine learning in predictive maintenance towards sustainable smart manufacturing in Industry 4.0. Sustainability. 2020;12(19):8211.
147 Trstenjak M, Opetuk T, Cajner H, Tosanovic N. Process planning in Industry 4.0—current state, potential and management of transformation. Sustainability. 2020;12(15):5878.
148. Narula S, et al. Applicability of Industry 4.0 technologies in the adoption of global reporting initiative standards for achieving sustainability. J Clean Prod. 2021;305:127141.
149. Enyoghasi C, Badurdeen F. Industry 4.0 for sustainable manufacturing: opportunities at the product, process, and system levels. Resour Conserv Recycl. 2021;166:105362.
150. Lim CH, et al. A review of Industry 4.0 revolution potential in a sustainable and renewable palm oil industry: HAZOP approach. Renew Sustain Energy Rev. 2021;135:110223.
151. Wang XV, Wang L. Digital twin-based WEEE recycling, recovery and remanufacturing in the background of Industry 4.0. Int J Prod Res. 2019;57(12):3892–902. https://doi.org/10.1080/00207543.2018.1497819.
152. Hofmann E, Rüsch M. Industry 4.0 and the current status as well as future prospects on logistics. Comput Ind. 2017;89:23–34.
153. Müller JM, Buliga O, Voigt K-I. Fortune favors the prepared: how SMEs approach business model innovations in Industry 4.0. Technol Forecast Soc Change. 2018;132:2–17.
154. Adamik A, Nowicki M. Pathologies and paradoxes of co-creation: a contribution to the discussion about corporate social responsibility in building a competitive advantage in the age of Industry 4.0. Sustainability. 2019;11(18):4954.
155. Gregori F, Papetti A, Pandolfi M, Peruzzini M, Germani M. Digital manufacturing systems: a framework to improve social sustainability of a production site. Procedia CIRP. 2017;63:436–42.
156. Waibel MW, Steenkamp LP, Moloko N, Oosthuizen GA. Investigating the effects of smart production systems on sustainability elements. Procedia Manuf. 2017;8:731–7.
157. Dallasega P, Rauch E, Linder C. Industry 4.0 as an enabler of proximity for construction supply chains: a systematic literature review. Comput Ind. 2018;99:205–25.
158. Javaid M, Haleem A. Critical components of Industry 5.0 towards a successful adoption in the field of manufacturing. J Ind Integr Manag. 2020;05(03):327–48. https://doi.org/10.1142/S2424862220500141.
159. Erboz G. How to define Industry 4.0: main pillars of Industry 4.0. Manag Trends Dev Enterp Glob Era. 2017;761:761–7.
160. Tsai W-H, Lai S-Y. Green production planning and control model with ABC under Industry 4.0 for the paper industry. Sustainability. 2018;10(8):2932.
161 Mabkhot MM, et al. Mapping Industry 4.0 enabling technologies into united nations sustainability development goals. Sustainability. 2021;13(5):2560.
162. Sarkis J, Zhu Q. Environmental sustainability and production: taking the road less travelled. Int J Prod Res. 2018;56(1–2):743–59. https://doi.org/10.1080/00207543.2017.1365182.
163. Branger J, Pang Z. From automated home to sustainable, healthy and manufacturing home: a new story enabled by the Internet-of-Things and Industry 4.0. J Manag Anal. 2015;2(4):314–32. https://doi.org/10.1080/23270012.2015.1115379.
164. dos Santos CH, de Queiroz JA, Leal F, Montevechi JAB. Use of simulation in the Industry 4.0 context: creation of a digital twin to optimise decision making on non-automated process. J Simul. 2020. https://doi.org/10.1080/17477778.2020.1811172.
165. Chalmeta R, Santos-deLeón NJ. Sustainable supply chain in the era of Industry 4.0 and big data: a systematic analysis of literature and research. Sustainability. 2020;12(10):4108.
166. Verma P, et al. Industry 4.0 in emerging economies: technological and societal challenges for sustainability. In: Applications and Challenges of Maintenance and Safety Engineering in Industry 4.0. IGI Global; 2020. p. 31–48. https://www.igi-global.com/chapter/industry-40-in-emerging-economies/255356. Accessed 17 Nov 2023.
167. Ustundag A, Cevikcan E. Industry 4.0: managing the digital transformation. In: Springer Series in Advanced Manufacturing. Cham: Springer International Publishing; 2018. https://doi.org/10.1007/978-3-319-57870-5.
168. Theorin A, et al. An event-driven manufacturing information system architecture for Industry 4.0. Int J Prod Res. 2017;55(5):1297–311. https://doi.org/10.1080/00207543.2016.1201604.
169. Upadhyay A, Mukhuty S, Kumar V, Kazancoglu Y. Blockchain technology and the circular economy: Implications for sustainability and social responsibility. J Clean Prod. 2021;293:126130. https://doi.org/10.1016/j.jclepro.2021.126130.
170. Zheng Z, Xie S, Dai H-N, Chen X, Wang H. Blockchain challenges and opportunities: a survey. Int J Web Grid Serv. 2018;14(4):352–75.

171 Kurniawan TA, Dzarfan Othman MH, Hwang GH, Gikas P. Unlocking digital technologies for waste recycling in Industry 4.0 era: a transformation towards a digitalization-based circular economy in Indonesia. J Clean Prod. 2022;357:131911. https://doi.org/10.1016/j.jclepro.2022.131911.
172 Di Carlo F, Mazzuto G, Bevilacqua M, Ciarapica FE. Retrofitting a process plant in an Industry 4.0 perspective for improving safety and maintenance performance. Sustainability. 2021. https://doi.org/10.3390/su13020646.
173. Samaranayake P, Ramanathan K, Laosirihongthong T. Implementing Industry 4.0—a technological readiness perspective. In: 2017 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM); 2017. p. 529–33. https://doi.org/10.1109/IEEM.2017.8289947.
174. do Cabrita MR, Duarte S. Addressing sustainability and Industry 4.0 to the business model. In: Information Resources Management Association, editor. Research anthology on cross-industry challenges of Industry 4.0. Hershey: IGI Global; 2021. p. 818–38. https://doi.org/10.4018/978-1-7998-8548-1.ch041.
175. Mohelska H, Sokolova M. Management approaches for Industry 4.0—the organizational culture perspective. Technol Econ Dev Econ. 2018;24(6):2225–40.
176. Felsberger A, Reiner G. Sustainable Industry 4.0 in production and operations management: a systematic literature review. Sustainability. 2020;12(19):7982.
177. Oluyisola OE, Sgarbossa F, Strandhagen JO. Smart production planning and control: concept, use-cases and sustainability implications. Sustainability. 2020;12(9):3791.
178. Munsamy M, Telukdarie A. Application of Industry 4.0 towards achieving business sustainability. In: 2018 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE; 2018. p. 844–8. https://ieeexplore.ieee.org/abstract/document/8607566/. Accessed 19 Nov 2023.
179. Çalık A. A novel Pythagorean fuzzy AHP and fuzzy TOPSIS methodology for green supplier selection in the Industry 4.0 era. Soft Comput. 2021;25(3):2253–65. https://doi.org/10.1007/s00500-020-05294-9.
180. Ivanov D, Dolgui A. A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. Prod Plan Control. 2021;32(9):775–88. https://doi.org/10.1080/09537287.2020.1768450.
181. Kamble SS, Gunasekaran A, Sharma R. Analysis of the driving and dependence power of barriers to adopt Industry 4.0 in Indian manufacturing industry. Comput Ind. 2018;101:107–19.
182. Mittal S, Khan MA, Romero D, Wuest T. A critical review of smart manufacturing & Industry 4.0 maturity models: implications for small and medium-sized enterprises (SMEs). J Manuf Syst. 2018;49:194–214.
183. Haseeb M, Hussain HI, Ślusarczyk B, Jermsittiparsert K. Industry 4.0: a solution towards technology challenges of sustainable business performance. Soc Sci. 2019;8(5):154.
184. Ibarra D, Ganzarain J, Igartua JI. Business model innovation through Industry 4.0: a review. Procedia Manuf. 2018;22:4–10.
185. Javaid M, Haleem A, Singh RP, Suman R. Significant applications of big data in Industry 4.0. J Ind Integr Manag. 2021;06(04):429–47. https://doi.org/10.1142/S2424862221500135.
186. Takhar SS, Liyanage K. The impact of Industry 4.0 on sustainability and the circular economy reporting requirements. Int J Integr Supply Manag. 2020;13(2/3):107. https://doi.org/10.1504/IJISM.2020.107845.
187. Gerlitz L. Design management as a domain of smart and sustainable enterprise: business modelling for innovation and smart growth in Industry 4.0. Entrep Sustain Issues. 2016;3(3):244.
188. Santos C, Mehrsai A, Barros AC, Araújo M, Ares E. Towards Industry 4.0: an overview of European strategic roadmaps. Procedia Manuf. 2017;13:972–9.
189. Nelles J, Kuz S, Mertens A, Schlick CM. Human-centered design of assistance systems for production planning and control: the role of the human in Industry 4.0. In: 2016 IEEE International Conference on Industrial Technology (ICIT), IEEE. 2016; p. 2099–104. https://ieeexplore.ieee.org/abstract/document/7475093/. Accessed 19 Nov 2023.
190. Zhang J, Ding G, Zou Y, Qin S, Fu J. Review of job shop scheduling research and its new perspectives under Industry 4.0. J Intell Manuf. 2019;30(4):1809–30. https://doi.org/10.1007/s10845-017-1350-2.
191. Fernández-Caramés TM, Fraga-Lamas P. A review on human-centered IoT-connected smart labels for the Industry 4.0. IEEE Access. 2018;6:25939–57.
192. Dassisti M, Semeraro C, Chimenti M. Hybrid exergetic analysis-LCA approach and the Industry 4.0 paradigm: assessing manufacturing sustainability in an Italian SME. Procedia Manuf. 2019;33:655–62.
193. Nahavandi S. Industry 5.0—a human-centric solution. Sustainability. 2019;11(16):4371.
194. Salimova T, Vukovic N, Guskova N. Towards sustainability through Industry 4.0 and Society 5.0. Int Rev. 2020;3–4:48–54.
195. Fonseca L, Amaral A, Oliveira J. Quality 4.0: the EFQM 2020 model and Industry 4.0 relationships and implications. Sustainability. 2021;13(6):3107.
196 Ramadan M, Salah B, Othman M, Ayubali AA. Industry 4.0-based real-time scheduling and dispatching in lean manufacturing systems. Sustainability. 2020;12(6):2272.
197 Müller JM. Antecedents to digital platform usage in Industry 4.0 by established manufacturers. Sustainability. 2019;11(4):1121.
198 Dzwigol H, Dzwigol-Barosz M, Miśkiewicz R, Kwilinski A. Manager competency assessment model in the conditions of Industry 4.0. Entrep Sustain Issues. 2020;7(4):2630.
199 Sołtysik-Piorunkiewicz A, Zdonek I. How society 5.0 and Industry 4.0 ideas shape the open data performance expectancy. Sustainability. 2021;13(2):917.
200 Facchini F, Oleśków-Szłapka J, Ranieri L, Urbinati A. A maturity model for logistics 4.0: an empirical analysis and a roadmap for future research. Sustainability. 2019;12(1):86.
201. Trappey AJC, Trappey CV, Fan C-Y, Hsu APT, Li X-K, Lee IJY. IoT patent roadmap for smart logistic service provision in the context of Industry 4.0. J Chin Inst Eng. 2017;40(7):593–602. https://doi.org/10.1080/02533839.2017.1362325.
202. Pilloni V. How data will transform industrial processes: crowdsensing, crowdsourcing and big data as pillars of Industry 4.0. Future Internet. 2018;10(3):24.

203. Diez-Olivan A, Del Ser J, Galar D, Sierra B. Data fusion and machine learning for industrial prognosis: trends and perspectives towards Industry 4.0. Inf Fusion. 2019;50:92–111.
204. Yang S, Aravind Raghavendra MR, Kaminski J, Pepin H. Opportunities for Industry 4.0 to support remanufacturing. Appl Sci. 2018;8(7):1177.
205. Blayone TJB, VanOostveen R. Prepared for work in Industry 4.0? Modelling the target activity system and five dimensions of worker readiness. Int J Comput Integr Manuf. 2021;34(1):1–19. https://doi.org/10.1080/0951192X.2020.1836677.
206 Asiimwe MM, De Kock IH. An analysis of the extent to which Industry 4.0 has been considered in sustainability or socio-technical transitions. South Afr J Ind Eng. 2019. https://doi.org/10.7166/30-3-2245.
207. Neumann WP, Winkelhaus S, Grosse EH, Glock CH. Industry 4.0 and the human factor—a systems framework and analysis methodology for successful development. Int J Prod Econ. 2021;233:107992. https://doi.org/10.1016/j.ijpe.2020.107992.