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# Sustainable Manufacturing in Industry 4.0 by Artificial Intelligent and Internet of Things, A Review

Mohsen SOORI*[1], Behrooz AREZOO[1]
[1] Amirkabir University of Technology /Department of Mechanical Engineering, Tehran, Iran

*Corresponding Author

***Abstract*— Artificial Intelligent (hereafter: AI), Internet of Things (hereafter: IoT) and data analytics are used to provide real-time resource utilization monitoring and optimization within Industry 4.0 era. As a result, waste is decreased and resource efficiency is improved which can minimize environmental impact and supports sustainability goals. By growing concerns of environmental issues, sustainability was converted to fundamental prerequisite of contemporary industrial systems. In order to present advanced models and methodologies of AI and IoT applications in sustainability enhancement of part manufacturing within Industry 4.0, the review of recent developments is presented in the study. It analyzes the applications of AI, IoT and data analytics in terms of resource optimization and decision-making regarding sustainability concerns of part manufacturing procedures. This study investigates how Industry 4.0 can be applied for sustainable manufacturing by improving resource efficiency, integrating renewable energy, allowing circular economy practices and promoting supply chain transparency. The study synthesizes data from recent research works in order to explain the contributions of smart manufacturing, predictive maintenance, virtual machining and blockchain supported supply chain management in terms of waste, energy usage and environmental impact minimization of advanced manufacturing. The article also discusses AI and IoT technology applications in terms of enhancing traceability, visibility, and efficiency within supply chain management processes. Applications of decentralized manufacturing, human-centric design, and collaborative industrial ecosystems are also presented and discussed. Also, key challenges including rising e-waste, data privacy threats, talent shortages and the demand of supporting legislative frameworks and resilient digital infrastructures are discussed in the study. Moreover, to provide the potential future research directions from AI and IoT applications in achieving sustainability within industry 4.0 paradigm, novel ideas are presented and discussed. As a result, the study provides practical insights and recommendations which enable researchers, industry stakeholders and lawmakers to analyze and develop sustainability strategies inside industrial contexts within Industry 4.0 era.***

***Keywords*— Industry 4.0, Sustainable manufacturing, Artificial Intelligent, Internet of Things**

## I. Introduction

As humanity navigates through the complexities of a rapidly changing world, the imperative to reconcile industrial progress with ecological responsibility has become increasingly critical. Despite all of the enthusiasm for scientific development in advanced manufacturing, sustainability is now considered as an important challenge of industrial production impacts to the environment (B. Singh & Kaunert, 2024). Environmental degradation, resource depletion, and climate change are a few of the important issues that require immediate attention and coordinated action. In this context, the fusion of Industry 4.0 with sustainability principles becomes a powerful force for significant transformation (Yan et al., 2018). So, the junction of sustainability and industry stands as a critical frontier in influencing the future of global economic and environmental landscapes (Paolanti et al., 2018). This requirement is reflected in the rise of Industry 4.0, a paradigm shift marked by the combination of Artificial Intelligent (AI), Internet of Things (IoT) sensors with conventional industrial procedures. At its foundation, Industry 4.0 heralds a new age of productivity and economic development by promising previously unheard-of levels of efficiency, connection, and cross-sector innovation (B. Singh & Nayyar, 2025).

This collaboration offers a rare chance to rethink industrial processes from a sustainable perspective, promoting a positive correlation between financial success and environmental conservation. Through the usage of digital innovation, data analytics, and automation, companies can reduce waste production,

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maximize resource use, and lessen their environmental impact (Maiurova et al., 2022). Furthermore, a more robust and regenerative industrial environment can be created by incorporating eco-friendly materials, circular economy ideas, and renewable energy sources into production processes. However, there are obstacles and challenges in the way of Industry 4.0's transition to sustainability enhancement of production prosses (Dhyani, 2021). The challenges of sustainable manufacturing can be considered as socioeconomic considerations, legal restrictions, and technological limitations. Moreover, attaining real sustainability involves a paradigm shift in corporate attitude, cultural norms, and stakeholder involvement throughout the entire spectrum (Johannsdottir & Davidsdottir, 2024).

Within the Industry 4.0 framework, sustainable manufacturing is made possible by AI and the IoT, which enable companies to run more precisely, efficiently, and responsibly (Bag & Pretorius, 2022). By combining intelligent sensors, real-time data analytics, and autonomous decision-making systems, AI and IoT allow manufacturers to decrease waste, cut energy consumption, and maximize the use of resources throughout the production lifecycle (Tyagi, Bhatt, Chidambaram, & Kumari, 2024). These technologies also help predictive maintenance, minimizing downtime and increasing equipment life while cutting needless material and energy usage (Patil, 2024). Additionally, supply chain transparency is improved and circular economy techniques like recycling, remanufacturing, and product lifetime tracking are made easier by AI-driven analytics. So, AI and IoT can help in order to construct cleaner, smarter, and more resilient industrial ecosystems for providing sustainable production within Industry 4.0 era (Zhao, Chen, & Bulis, 2025).

The relationship between sustainability and Industry 4.0 using AI and IoT in an ever-changing environment are discussed in the study by analyzing the opportunities, limitations, and revolutionary potential that come with their confluence. As a result, through a comprehensive analysis of case studies, best practices, and emerging trends of sustainable manufacturing using AI and IoT are also presented and disused in the study. Industry 4.0 represents a significant evolution in industrial practices, focusing not just on efficiency and productivity but also on sustainability and human-centric approaches. Here's how sustainability is approached from the perspective of Industry 4.0:

1. Circular Economy Integration: The circular economy, which emphasizes resource efficiency, waste reduction, and material reuse or recycling whenever feasible, is encouraged by Industry 4.0. This entails creating long-lasting, repairable, and recyclable items as well as using reverse logistics to retrieve and restore old goods (Jensen, 2025).

2. Collaborative Networks: Industry 4.0 places a strong emphasis on cooperation between producers, distributors, suppliers, and customers along the whole value chain. Businesses can streamline industrial processes, save waste, and jointly solve environmental concerns by more efficiently exchanging information and resources (Hegab, Shaban, Jamil, & Khanna, 2023).

3. Advanced Technologies for Sustainability: Industry 4.0 uses advanced technologies like blockchain, AI, and IoT to track and improve emissions, energy use, and resource use. These technologies enable real-time data evaluation and decision-making, leading to more ecologically friendly operations.

4. Decentralized Manufacturing: Since Industry 4.0 decentralizes manufacturing, local production and customization are made possible. As a result, there is less demand for long-distance freight transportation, which lowers carbon emissions and the amount of resources used in logistics (Lu & Li, 2023).

5. Human-Centric Design: Industry 4.0 places a strong emphasis on human well-being and safety. Sustainable practices include designing ergonomic workspaces, reducing exposure to hazardous materials, and providing training and support for employees to adapt to changing roles in the evolving industrial landscape.

6. Resilience and Adaptability: The significance of resilience in the face of social and environmental crises is recognized by Industry 4.0. In order to respond swiftly to disturbances like supply chain outages, natural catastrophes, or regulatory changes, businesses are urged to include flexibility into their operations (Nweje & Taiwo, 2025).

7. Transparency and Accountability: Throughout the supply chain, Industry 4.0 encourages accountability and openness. In order for customers to make educated decisions and hold businesses

responsible for their activities, businesses are required to reveal information about their labor practices, social responsibility initiatives, and environmental effect (Camilleri, 2022).

Incorporating these concepts into their operations allows industries to enhance their environmental performance while simultaneously generating long-term benefits for society and future generations. The shift to more sustainable and human-centered industrial practices, known as Industry 4.0, aligns environmental preservation and social responsibility with economic growth.

Soori et al. (Soori, Arezoo, & Habibi, 2013, 2014, 2016, 2017) recommended methods for virtual machining to analyze and develop CNC production in virtual settings. Soori et al. (Soori, Asmael, & Solyalı, 2020) discussed the most recent advancements in friction stir welding techniques in an attempt to evaluate and improve the process' effectiveness during component manufacturing.

Soori and Asamel (Soori & Asmael, 2021d) examined ways to minimize residual stress and displacement error during five-axis milling operations for turbine blades by utilizing virtual machining equipments. Soori and Asmael (Soori & Asmael, 2021b) pondered the possibility of monitoring and reducing the cutting temperature while using virtualized machining procedures to mill materials that are difficult to cut. Soori et al. (Soori, Asmael, Khan, & Farouk, 2021) suggested that when milling turbine blades in five axis milling operations, surface characteristics be improved by using a sophisticated virtual machining technique.

Soori and Asmael (Soori & Asmael, 2021c) created virtual milling processes to reduce deformation error in five-dimensional impeller blade milling. Soori (Soori, 2019) provided virtual innovation in an attempt to learn more about and look into the process of creating parts in virtual environments. To analyze the applications of virtual machining in part manufacturing process, a review is presented by Soori and Arezoo (Soori & Arezoo, 2020).

Soori and Asmael (Soori & Asmael, 2022) compiled the results of recent studies from the literature to evaluate and improve the parameter approach for machining process simulation. Soori et al. (Soori, Arezoo, & Dastres, 2023d) looked at how artificial intelligence and machine learning could assist CNC machine tools become more profitable and efficient in the element production industry. To improve the functionality of machined parts, Soori and Arezoo (Soori & Arezoo, 2022b) explored the issue of calculating and minimizing residual stress during the milling process. To increase the lifespan of the cutters used in machining operations, Soori and Arezoo (Soori & Arezoo, 2022a) investigated many methods for predicting tool wear. Soori and Asmael (Soori & Asmael, 2021a) investigated the application of computer-assisted procedure scheduling to boost component manufacturing methods' productivity.

Soori and Arezoo (Soori & Arezoo, 2023b) have improved 5-axis CNC milling techniques' accuracy by fixing mistakes in geometry, temperature, tool motion, and measurements. Soori et al. (Soori, Arezoo, & Dastres, 2023a) studied recent advances in the literature to analyze and modify the effects of neural networks, deep learning, and machine learning on advanced robotics.

To determine whether the milling process's cutting specifications have an impact on the tool's life and the temperature at which the cutting occurs, Soori and Arezoo (Soori & Arezoo, 2023c) created an application for a virtual machining technique. Soori and Arezoo (Soori & Arezoo, 2023d) examined the effects of coolant changes on cutting temperature, tool selection, and surface roughness during the turning of Ti6Al4V material. Soori (Soori, 2023a) examines and modifies composite materials and structures by doing a review of current developments from published research. Soori et al. (Soori, Arezoo, & Dastres, 2023c) investigated strategies to improve industrial quality control and streamline the manufacturing of parts. 4.0 smart factories that use IoT applications. To reduce the amount of harm that is done to drilling tools, Soori and Arezoo (Soori & Arezoo, 2023a) studied a virtual machining. To enhance the overall quality of the product produced by water jet cutting using an abrasive, Soori and Arezoo (Soori & Arezoo, 2023e) reduced surface roughness and residual stress. In order to improve the precision of turbine blade five-axis machining operations, Soori (Soori, 2023b) detects and corrects any possible errors in the deformation. To assess and improve the precision of CNC machining procedures and parts, Soori and Arezoo (Soori & Arezoo, 2023f) examined the application of finite element analysis to CNC machine tool customization. To assess and maximize the energy utilization of industrial robots, Soori et al. (Soori, Arezoo, & Dastres, 2023e) examined several methods for optimizing energy consumption.

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Soori et al. (Soori, Arezoo, & Dastres, 2023f) carried out research work in order to evaluate and enhance the manufacturing process for Industry 4.0 components by looking at the disadvantages and advantages of virtual manufacturing methodologies. Soori et al. (Soori, Arezoo, & Dastres, 2023b) are investigating the use of AI in high-tech manufacturing supply chain management integration.

The existing literature extensively underlines the significance of Industry 4.0 technologies in promoting sustainability; while most studies remain fragmented, concentrating on individual technologies rather than their overall influence on sustainable manufacturing systems. Despite detailed talks on IoT, AI, digital twins and circular economy practices, there is a dearth of unifying frameworks which statistically measure how these technologies can enhance environmental, economic, and social performances of advanced manufacturing. Furthermore, the conversion of theoretical developments into useful commercial applications is hampered by a lack of empirical validation and real-world case studies. This gap emphasizes the need for holistic, data-driven models and cross-sector studies to enable effective adoption of Industry 4.0 for sustainable manufacturing. Unlike earlier assessments that address isolated technologies and specific sustainability pillars, this work presents a multidimensional framework integrating resource efficiency, circular economy principles, and supply chain transparency. So, the study is positioned as a forward-looking blueprint for sustainable industrial transformation as it also highlights important research gaps and future directions.

To present the study and capture the evolution of sustainable manufacturing within Industry 4.0, leading academic databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, and Google Scholar are considered for analyzing by focusing on studies published between 2010 and 2025. This review highlights important research gaps and issues that need more study by synthesizing academic literature, case studies, and industry reports. As a result, this study provides an innovative and comprehensive synthesis of novel technologies such as IoT, AI, blockchain, and digital twins in industry 4.0 era order to revolutionize sustainable manufacturing.

In the framework of the industry 4.0 paradigm, this study contributes to the expanding discussion on how blockchain technology and the IoT can transform sustainable supply chain management. It looks at how increased accountability and traceability could maximize resource usage, reduce carbon footprints, and promote moral conduct. Therefore, this study offers practical insights and recommendations for researchers, industry stakeholders, and authorities trying to manage the complicated relationship between Industry 4.0 and sustainability and to build a more resilient, inclusive, and ecologically responsible industrial future.

## II. Resource efficiency

Industry 4.0, the current industrial technology trends of automation and data exchange, is based on the core principles of resource efficiency and sustainability. The goal of Industry 4.0 is to improve operations and maximize consumption of resource while reducing trash and its impact on the environment (Shabur, 2024). The integration of digital technologies like cloud computing, big data analytics, artificial intelligence, and the IoT are key elements of this strategy. Here are some key ways in which Industry 4.0 promotes resource efficiency and sustainability:

1. Predictive Maintenance: Real-time equipment health monitoring is made possible by IoT sensors integrated into machinery, which allows predictive maintenance to save energy use and avoid malfunctions. This saves costs by extending the lifespan of machines and decreasing downtime.
2. Smart Manufacturing: AI-powered Algorithms examine manufacturing data in order to find inefficiencies and streamline procedures. Manufacturers can reduce resource usage and preserve product quality by dynamically modifying variables like temperature, pressure, and speed.
3. Supply Chain Optimization: Blockchain technology, which provides transparency and traceability across the supply chain, helps organizations to more accurately forecast demand and manage stocks in order to reduce waste and ethical material acquisition. (Khanfar, Iranmanesh, Ghobakhloo, Senali, & Fathi, 2021).

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4. Energy Management: Data analytics are used by energy management systems and smart grids to maximize energy use in manufacturing operations. In order to lower operating expenses and the carbon footprint, this includes demand response plans, energy-efficient machinery, and the integration of renewable energy sources.
5. Circular Economy: Industry 4.0 makes it possible to monitor the lifespan of products, remanufacture them, and recycle them, which helps to move towards a circular economy model. By allowing for component disassembly and reuse, IoT-enabled goods can minimize waste production and raw material consumption (Trstenjak, Opetuk, Cajner, & Tosanovic, 2020).
6. Collaborative Robots (Cobots): In manufacturing operations, collaborative robots assist human workers, increasing output and safety while using less resources. Cobots are designed to be energy-efficient and adaptable, allowing for flexible production without sacrificing efficiency.
7. Data-Driven Decision Making: Manufacturers can improve resource allocation, production scheduling, and inventory management by using actionable insights from big data analytics into resource consumption trends (Vacchi, Siligardi, Cedillo-González, Ferrari, & Settembre-Blundo, 2021). Industry 4.0 applications in resource efficiency is presented in Figure 1.

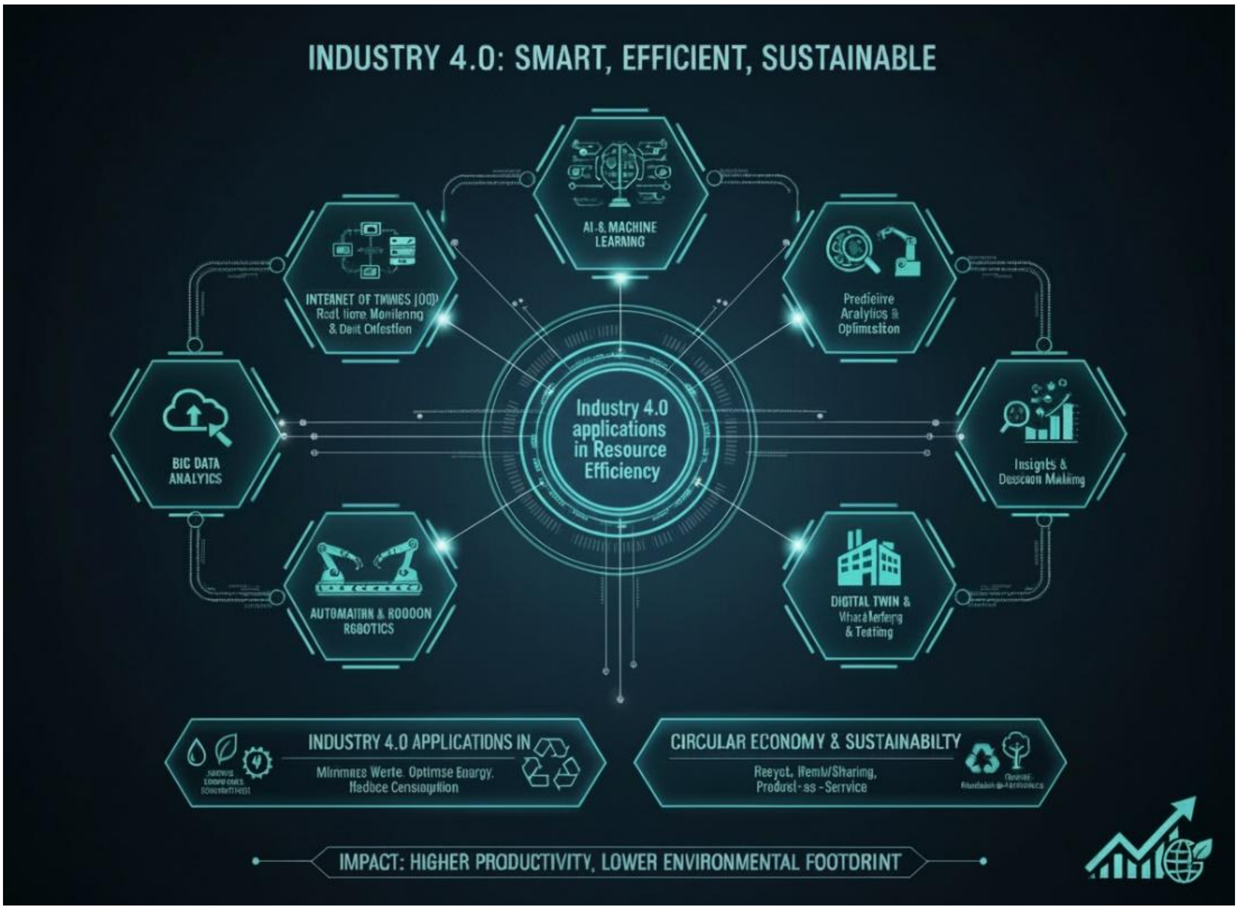


**Figure 1** Industry 4.0 applications in resource efficiency

Businesses can significantly enhance sustainability and resource efficiency by adopting Industry 4.0 concepts and utilizing cutting-edge technology, which will eventually help to create a more sustainable and economically viable future.

## III. Renewable Energy

Industry 4.0's energy management platforms and smart grids allow for the seamless integration of renewable energy suppliers. This contributes to the accomplishment of sustainability objectives by encouraging the switch to greener energy sources and lowering dependency on fossil fuels. Sustainability projects must incorporate renewable energy. Let's break it down:

1. Renewable Energy Sources: These consist of geothermal, biomass, hydroelectric, wind and solar energy. They are crucial to the battle against climate change since, in contrast to fossil fuels, they are sustainable and release few or no greenhouse gasses (Bigliardi, Bottani, & Casella, 2020).
2. Integration into Industry 4.0: When industrial processes are continuously automated and digitalized via the use of robotics, big data analytics, AI, and IoT are applied.
3. Industry 4.0's integration of renewable energy entails using these technologies to maximize energy use, improve efficiency, and lessen environmental effects (Beliatis, Jensen, Ellegaard, Aagaard, & Presser, 2021).
4. Smart Grids: Creating smart grids is one method of incorporating energy from renewable sources into Industry 4.0. These grids utilize advanced communication and control technologies to manage the flow of electricity more efficiently, incorporating renewable sources such as solar and wind power. Smart grids enable real-time monitoring and adjustment of energy distribution in order to improve reliability and resilience.
5. Energy Storage: Another crucial element is the development of energy storage technologies, such as thermal storage, pumped hydro storage, and batteries. By storing extra energy during times of high generation or low demand and releasing it when needed, these devices assist in order to lessen the intermittent nature of renewable energy sources. A steady and dependable power supply is ensured by incorporating energy storage into Industry 4.0 machinery (Javaid, Haleem, Singh, & Suman, 2022).
6. Predictive Analytics: Optimizing the integration of renewable energy is greatly aided by artificial intelligence and big data analytics. Predictive analytics can improve energy production and consumption, lowering costs and limiting environmental effect, by examining large volumes of data from renewable energy sources, weather predictions, energy demand patterns, and equipment performance (Devaraj, Madurai Elavarasan, Shafiullah, Jamal, & Khan, 2021).
7. Decentralized Energy Systems: Industry 4.0 facilitates the decentralized energy development of systems where renewable energy sources are integrated at the local level, closer to the point of consumption. This approach reduces transmission losses and enhances energy security, empowering businesses and communities to generate their own clean energy (Chen, 2017).
8. Policy and Regulatory Frameworks: Effective integration of renewable energy into Industry 4.0 requires supportive policy and regulatory frameworks. Governments can incentivize investment in renewable energy technologies, promote research and development, and establish standards and regulations to ensure the smooth integration of renewables into industrial processes.

Overall, achieving sustainability objectives, cutting carbon emissions, and building a more robust and effective energy system for the future all depend on incorporating renewable energy into Industry 4.0.

## IV. Circular Economy Practices

Through the facilitation of product lifetime monitoring, remanufacturing, and recycling, Industry 4.0 makes it possible to implement the concepts of the circular economy. Supply chains become more transparent thanks to technologies like blockchain and RFID, which improve material and waste stream management (Dastres, Soori, & Asmael, 2022). Innovative solutions for sustainability across a range of sectors are being created by the convergence of Industry 4.0 technology and circular economy principles. Here are some ways they intersect:

1. Resource Efficiency through IoT and AI: Real-time resource utilization monitoring and optimization are made possible by Industry 4.0 technology such as AI algorithms and IoT sensors. A fundamental tenet of the circular economy, this enables firms to optimize resource efficiency and reduce waste.
2. Product Lifecycle Management (PLM): Combining PLM systems with Industry 4.0 technologies enhances management of product lifecycle and tracking. This includes design, manufacture, usage, and end-of-life stages. Optimizing product lifecycles can help businesses reduce waste and extend product lifespans, which aligns with the principles of the circular economy (Park & Li, 2021).
3. Additive Manufacturing (3D Printing): On-demand creation of items and parts is made possible by additive manufacturing technology which can eliminate the demand of surplus inventory and mass production. By reducing overproduction and facilitating product customization, repair, and remanufacturing, this supports the circular economy (Jung, Kara, Nie, Simpson, & Whitefoot, 2023).
4. Closed-Loop Supply Chains: Industry 4.0 systems facilitate the creation of closed-loop supply chains where materials are continuously recycled and reused. IoT sensors can track materials throughout the supply chain, enabling better sorting, recycling, and remanufacturing processes. This minimizes waste and reduces the need for virgin resources (Mtetwa, 2024).
5. Blockchain for Traceability and Transparency: Blockchain technology provides a transparent and immutable ledger that can track the origin, usage, and disposal of products and materials. By integrating blockchain into supply chains, companies can ensure the traceability of materials, enabling better accountability and incentivizing sustainable practices (Khanfar et al., 2021).
6. Sharing Platforms and Product-as-a-Service (PaaS): Product as a service model and sharing platforms are growing in popularity because to Industry 4.0 technologies, which let consumers access products and services whenever they need them instead of buying them all at once. This shift from ownership to access reduces resource consumption and promotes sharing and product reuse, two essential elements of the circular economy (Prashar, Vasudev, & Bhuddhi, 2023).
7. Predictive Maintenance: Predictive maintenance can minimize downtime and extend the life of products and machinery by employing AI and algorithms of machine learning to anticipate equipment failures before they occur. By prolonging the usable life of assets, businesses can save waste and improve resource efficiency (Jiang et al., 2022).
8. Sustainable Supply Chain Management: Industry 4.0 technologies enable more efficient and transparent supply chain management practices, including supplier collaboration, risk assessment, and optimization of transportation routes. By ensuring the sustainability of the entire supply chain, companies can minimize environmental impact and enhance circularity (Sudusinghe & Seuring, 2022).

By leveraging Industry 4.0 technologies in conjunction with circular economy principles, businesses can drive innovation, improve resource efficiency and foster sustainability across their operations and supply chain.

## V. Smart Manufacturing

Smart manufacturing processes are made possible by Industry 4.0, where linked systems interact and change in real time. This reduces overproduction and inventory waste while increasing production flexibility and enabling customized, on-demand manufacturing (Lakshmanan, Nyamekye, Virolainen, & Piili, 2023). Smart manufacturing and Industry 4.0 are revolutionizing the industrial landscape by promoting sustainability initiatives in addition to increasing production and efficiency (Jamwal, Agrawal, Sharma, & Giallanza, 2021). Here's how:

1. Resource Optimization: Smart manufacturing employs advanced technologies like IoT sensors, AI-driven analytics, and machine learning to optimize resource usage. By monitoring energy, water, and material consumption in real-time, industries can identify areas for improvement and minimize waste (Zheng et al., 2018).

2. Predictive Maintenance: Predictive maintenance, in which machinery and equipment are continually monitored to foresee malfunctions before they happen, is made possible by Industry 4.0 technology (Pech, Vrchota, & Bednář, 2021). By extending asset lifespan, preventing needless resource consumption during repairs, and reducing downtime, this promotes sustainability by reducing resource waste (Karki, Basnet, Xiang, Montoya, & Porras, 2022).
3. Energy Efficiency: Energy-efficient technologies and procedures, including renewable energy sources, smart grids, and energy-efficient machinery, are integrated into smart manufacturing. Businesses can save operating expenses and their carbon impact by optimizing energy use throughout the production process (Matsunaga, Zytkowski, Valle, & Deschamps, 2022).
4. Supply Chain Transparency: Industry 4.0 enables more transparency and traceability across the supply chain. Using technologies like blockchain and the IoT, businesses can track the flow of raw materials from the point of origin to the finished product in terms of ensuring ethical sourcing practices and minimizing their adverse environmental consequences (Mubarik, Raja Mohd Rasi, Mubarak, & Ashraf, 2021).
5. Circular Economy Initiatives: By encouraging recycling, remanufacturing, and product lifetime management, smart manufacturing aids in the shift to a circular economy. Industries can reduce waste and resource depletion and help create a more sustainable manufacturing ecosystem by designing goods with disassembly and recyclability in mind (Yin, Luo, & Luo, 2018).
6. Data-Driven Decision Making: Industry 4.0 allows businesses to optimize operations for sustainability by relying on data-driven decision-making processes. Businesses can find areas for improvement and carry out focused interventions to lessen their impact on the environment by evaluating vast amounts of data from several sources, such as supply chains, industrial processes, and environmental issues (Javaid, Haleem, Singh, Suman, & Gonzalez, 2022).
7. Collaborative Robotics: Collaborative robots, or cobots, are increasingly being integrated into manufacturing processes to work alongside human workers safely. Cobots can improve efficiency, flexibility, and safety while reducing energy consumption and waste (Molęda, Małysiak-Mrozek, Ding, Sunderam, & Mrozek, 2023).
8. Smart Packaging: Smart manufacturing enables the development of intelligent packaging solutions equipped with sensors and IoT technology. These packages can monitor product conditions such as temperature, humidity, and freshness, helping to reduce food waste and improve product quality throughout the supply chain (A. Singh, Madaan, Hr, & Kumar, 2023).

In addition to increasing their competitiveness, industries can help to create a more sustainable and ecologically conscious future by adopting Industry 4.0 technology and smart manufacturing principles.

## VI. Optimized Production Processes

Autonomous systems and AI-driven predictive maintenance streamline manufacturing procedures, lowering emissions and energy use while increasing output. This optimization maximizes output efficiency while limiting resource inputs, which is in line with sustainability aims. In the context of Industry 4.0, optimizing manufacturing processes for sustainability is an essential undertaking for contemporary industries (Davis, Edgar, Porter, Bernaden, & Sarli, 2012). Here's how these two concepts intersect and some strategies for achieving them:

1. Integration of Digital Technologies: Industry 4.0 places a strong emphasis on the integration of digital technologies, including as automation, AI, big data analytics, and the IoT. Utilizing these technologies can enhance industrial operations for sustainability by reducing waste, boosting energy efficiency and consuming fewer resources (Hegab et al., 2023).
2. Data-driven Decision Making: Manufacturers can discover more about energy use, material flow, and environmental effect by gathering and evaluating real-time data from several sensors and linked

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devices during the manufacturing process. This data can inform decision-making processes in order to improve sustainability performance (Ghashghaee, 2016).

3. Predictive Maintenance: Implementing predictive maintenance strategies using IoT sensors and AI algorithms can be applied to minimize downtime, reduce energy consumption, and extend the lifespan of machinery and equipment in terms of contributing to both sustainability and operational efficiency.
4. Resource Optimization: Advanced analytics and AI can optimize resource allocation by dynamically adjusting production schedules, inventory levels, and supply chain logistics based on factors such as energy prices, raw material availability, and environmental regulations (Gawusu et al., 2022).
5. Integration of Renewable Energy: Industry 4.0 has enabled the integration of renewable energy sources, such wind and solar, into production procedures (Mastrocinque, Ramírez, Honrubia-Escribano, & Pham, 2022). By optimizing the use of renewable energy, smart grids and energy management systems can lower carbon emissions and dependency on fossil fuels.
6. Circular Economy Principles: Industry 4.0 technologies have the potential to facilitate the transition to a circular economy model by facilitating the reuse, remanufacturing, and recycling of products and resources. Digital monitoring and tracing systems can provide transparency and accountability across the course of the product's life (de Assis Dornelles, Ayala, & Frank, 2022).
7. Collaborative Supply Chain Management: Through cooperation among supply chain participants made possible by digital platforms and blockchain technology, sustainability norms and practices can be made more transparent, traceable, and accountable (Gligor et al., 2022).
8. Employee Engagement and Training: Investing in employee training and engagement programs focused on sustainability and digital literacy can empower workers to identify opportunities for improvement and contribute to the ongoing optimization of production processes (Ashima et al., 2021).

As a result, optimized manufacturing processes can increase added values of produced parts and sustainability of part production by applying AI and IoT as Industry 4.0 technologies.

## VII. Decentralized Manufacturing

Industry 4.0 facilitates decentralized manufacturing through concepts like additive manufacturing and distributed production networks. This decentralization can reduce transportation-related emissions and resource consumption by enabling localized production, thus enhancing sustainability. Decentralized manufacturing is a concept that's gaining traction, especially in the concepts of sustainability and Industry 4.0. The applications of decentralized manufacturing within sustainability enhancement of industry 4.0 can be presented as:

1. Decentralization: Conventional manufacturing frequently depends on centralized production facilities, in which products are manufactured in large quantities in one place before being sent all over the world. Conversely, smaller-scale production facilities located nearer the place of consumption are a feature of decentralized industry. Long-distance transportation is less necessary as a result, which lowers energy consumption and carbon emissions (Eisenkopf & Burgdorf, 2022).
2. Sustainability: Decentralized manufacturing can contribute significantly to sustainability efforts. By producing goods closer to where they're consumed, it reduces the environmental impact associated with transportation, such as greenhouse gas emissions from trucks, ships, or airplanes (Al-Ghussain, Alrbai, Al-Dahidi, & Lu, 2024). Additionally, decentralized manufacturing can enable the use of local materials and resources, further reducing the carbon footprint of production (Ching, Ghobakhloo, Iranmanesh, Maroufkhani, & Asadi, 2022).
3. Industry 4.0: Industry 4.0 is the term used to describe how smart technology is continuously changing conventional manufacturing and industrial processes. Decentralized manufacturing optimizes production processes by utilizing Industry 4.0 technology, including robots, automation, IoT devices,

and data analytics (Ashima et al., 2021; Jamwal et al., 2021). Smaller batch sizes, on-demand production, and customization are all made possible by these technologies, which also make manufacturing processes more adaptable and efficient and support sustainable practices (Varghese, Ande, Mahadasa, Gutlapalli, & Surarapu, 2023).

4. Advantages: Decentralized manufacturing offers several advantages beyond sustainability. It can enhance supply chain resilience by reducing dependency on centralized facilities vulnerable to disruptions like natural disasters as well as geopolitical tensions. Moreover, it fosters innovation and entrepreneurship by lowering the barriers to entry for smaller manufacturers and startups. Additionally, decentralized manufacturing can promote economic development by creating local job opportunities and supporting regional economies (Khambule, 2021).
5. Challenges: Decentralized manufacturing has drawbacks despite its possible advantages. These include handling supply chain complexity, maintaining quality control and uniformity across several dispersed operations, and attending to legal and intellectual property issues. Furthermore, major expenditures in infrastructure, technology, and employee training could be necessary in order to make switch from centralized to decentralized production (Helmrich et al., 2021).

Overall, decentralized manufacturing represents a promising paradigm shift towards more sustainable, resilient, and agile production systems, enabled by advancements in Industry 4.0 technologies. As a result, by leveraging local resources, minimizing transportation emissions, and empowering smaller-scale producers, the decentralized manufacturing has the potential to drive positive environmental impacts, social, and economic outcomes within industry 4.0 era.

## VIII. Sustainable Supply Chains

Blockchain technology and digital twins improve supply chain transparency and visibility, guaranteeing adherence to sustainability guidelines and facilitating ethical sourcing methods. Throughout the supply chain, this openness encourages sustainability and builds stakeholder confidence. Achieving environmental and social sustainability goals requires sustainable supply chains, which also provide operational resilience and efficiency. The concept of sustainable supply chains takes on new meanings and opportunities in the context of Industry 4.0, which emphasizes the integration of digital technology into supply chain and manufacturing processes (Chauhan et al., 2022). Here are some key points regarding sustainable supply chains in the context of Industry 4.0:

1. Visibility and Transparency: IoT sensors, blockchain, and sophisticated analytics are examples of Industry 4.0 technologies that offer previously unheard-of supply chain operational insight. This visibility promotes accountability and transparency by allowing businesses to monitor the social and environmental effects of their supply chains, from the procurement of raw materials to the disposal of end-of-life products (Kumar Singh, Chauhan, & Sarkar, 2022).
2. Efficiency and Optimization: Industry 4.0 technologies optimize supply chain processes, reducing waste, energy consumption, and emissions. For example, predictive analytics can optimize transportation routes, reducing fuel consumption and carbon emissions, while smart manufacturing technologies minimize resource usage and improve product quality (Enyejo et al., 2024).
3. Collaboration and Resilience: Industry 4.0 makes it possible for supply chain partners to work together more closely by providing platforms that make communication and data exchange easier. This collaboration enhances supply chain resilience by enabling rapid response to disruptions, whether they are caused by natural disasters, geopolitical events and changing consumer demands (Patel, 2023).
4. Circular Economy Principles: The circular economy, which keeps commodities in use for as long as possible through recycling, remanufacturing, and reuse, is made easier to employ in supply chains by Industry 4.0. Digital twins and IoT-enabled product tracking can help with the reverse logistics

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procedures required to put circular supply chain concepts into practice (Jum'a, Ikram, & Jabbour, 2024).

5. Ethical Sourcing and Compliance: Industry 4.0 technologies can help companies ensure ethical sourcing practices by proposing real-time monitoring of supplier activities and adherence to labor and environmental standards. Blockchain, for instance, can create immutable records of transactions, certifying the origin and sustainability credentials of raw materials.
6. Innovation and Continuous Improvement: Industry 4.0 fosters innovation within supply chains in terms of enabling companies to experiment with new sustainable technologies and business models. Continuous monitoring and data-driven insights support ongoing improvement initiatives can provide capabilities in order to iteratively enhance the sustainability of their supply chains (Bag, Srivastava, Cherrafi, Ali, & Singh, 2024). Applications of Blockchain technology and digital twins in sustainable supply chain management processes is shown in the Figure 2.

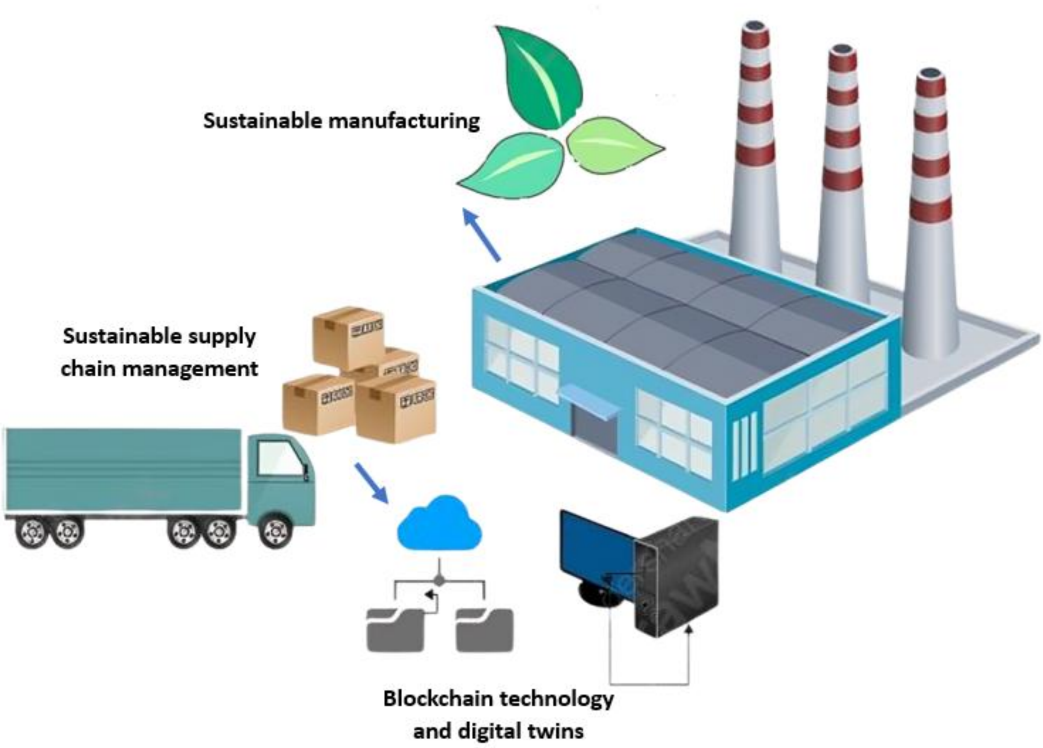


**Figure 2:** Applications of Blockchain technology and digital twins in sustainable supply chain management processes

In summary, Industry 4.0 presents unprecedented opportunities for advancing sustainability within supply chains by leveraging digital technologies to enhance visibility, efficiency, collaboration, and innovation. Embracing these technologies can help companies build resilient, ethical, and environmentally responsible supply chains that are essential for a sustainable future.

## IX. Resilience and Adaptability

Industry 4.0 technologies enhance the resilience and adaptability of industrial systems to environmental changes and disruptions. Businesses can anticipate and reduce environmental hazards by using predictive modeling and real-time data analytics, guaranteeing sustainability over the long run. Navigating the intricacies of Industry 4.0 while maintaining sustainability requires resilience and agility. There are advantages and disadvantages to Industry 4.0, which is defined by the implementation of digital technology into production and manufacturing processes. Here's how resilience and adaptability play crucial roles:

1. Navigating Technological Disruptions: Industry 4.0 is characterized by rapid technological advancements including automation, AI, and IoT. Resilience is the capacity to withstand disruptions caused by new technology, whereas adaptability is the ability to swiftly integrate new technologies into existing processes (Dwivedi et al., 2024).
2. Addressing Environmental Concerns: Sustainability is a key consideration in Industry 4.0, given its potential environmental impacts. Resilience requires developing systems and practices that minimize resource consumption and waste generation. Adaptability involves embracing renewable energy sources, implementing circular economy principles and designing products for longevity and recyclability.
3. Managing Supply Chain Dynamics: Industry 4.0 reshapes traditional supply chains through digitization and interconnectedness. To be resilient, supply chain networks must be strong enough to survive shocks like cyberattacks, natural catastrophes, and geopolitical unrest. Adaptability in supply chain management refers to the use of technologies such as blockchain to increase transparency and agility.
4. Empowering Workforce: The workforce of Industry 4.0 needs to be resilient and adaptable. Resilience involves fostering a culture of continuous learning and skill development to cope with evolving job roles and technological changes. Adaptability entails embracing new ways of working, such as remote collaboration, flexible scheduling, and human-robot collaboration (Eswaran, Eswaran, Eswaran, & Murali, 2024).
5. Promoting Innovation: Resilience and adaptability are essential for fostering innovation in Industry 4.0. Resilience allows organizations to experiment, learn from failures, and iterate their approaches. Adaptability enables them to pivot quickly in response to market dynamics and emerging opportunities, driving continuous innovation in products, services, and business models (Ngu, Lee, & Osman, 2020).
6. Ensuring Ethical Considerations: As technology permeates every aspect of industry, resilience involves upholding ethical standards and ensuring responsible use of data and AI. Adaptability requires organizations to proactively address ethical concerns, such as privacy, bias, and algorithmic accountability, through robust governance frameworks and stakeholder engagement (Bahangulu & Owusu-Berko, 2025).

In summary, resilience and adaptability are foundational principles for achieving sustainability in the context of Industry 4.0. By cultivating these qualities at organizational, technological, and societal levels, businesses can thrive amidst disruptions, mitigate environmental impacts, empower their workforce, drive innovation and uphold ethical standards in the digital marketing.

## X. Human-Centic Approach

Even though Industry 4.0 places a strong emphasis on automation and digitization, sustainable practices still require a human-centric approach. Organizations can cultivate a sustainable culture by investing in staff training, well-being, and ethical issues. In the context of Industry 4.0, a human-centric approach to sustainability highlights the significance of taking into account not just technical developments and economic progress, but also the well-being of individuals, communities, and societies (Nguyen & Batel, 2021). Here's how this approach might manifest:

1. Worker Empowerment: putting employee empowerment first by giving them the skills and resources they need to adjust to changing technology. To guarantee that staff members are prepared to manage new jobs and technology, this can involve reskilling and upskilling initiatives (Cvetkovski & Tomanovic, 2024).

2. Health and Safety: Ensuring that technological development in Industry 4.0 prioritize the health and safety of workers. This might involve the implementation of advanced safety protocols, ergonomic designs for workspaces, and monitoring systems to prevent accidents and injuries (Michalos et al., 2015).
3. Inclusive Design: Designing products, services, and technologies with inclusivity in mind to ensure that they are accessible and usable by all individuals, regardless of their abilities or background. This can help prevent the marginalization of certain groups and promote diversity and inclusion within the workforce (Hoffmann et al., 2020).
4. Community Engagement: interacting with local communities to learn about their requirements and worries about Industry 4.0 adoption and sustainable development. To make sure that development projects are in line with community interests, this can entail working with community leaders, conducting outreach programs, and asking for input (Ridzi & Prior, 2023).
5. Ethical Considerations: integrating moral issues into the decision-making procedures related to Industry 4.0 technology deployment. This entails dealing with concerns like algorithmic bias, data privacy, and the possible effects of automation on job prospects (Sohaib, Mushtaq, & Uddin, 2021).
6. Lifelong Learning: encouraging a culture of continuous development and lifelong learning to help people adjust to shifting technology environments throughout the course of their careers. This can entail making educational materials, mentorship programs, and chances for both professional and personal growth accessible (Sanchez, 2019).

By embracing a human-centered strategy for Industry 4.0 sustainability, organizations can not only drive technological innovation and economic growth but also ensure that these advancements are aligned with the broader goals of social responsibility, equity, and environmental stewardship.

## XI. Regulatory Compliance

Industry 4.0 can assist companies in meeting increasingly stringent environmental regulations by providing tools for monitoring and reporting emissions, waste, and other sustainability metrics. Compliance with these regulations not only mitigates legal risks but also fosters a positive reputation for sustainability leadership. Regulatory compliance is a critical aspect of sustainability initiatives, especially in regard to Industry 4.0 (Lopes, Estevão, & Toth-Peter, 2023). Industries must make sure that their operations comply with social and environmental norms while they embrace integrated technologies like automation, IoT, and AI in order to improve productivity and streamline processes. Here are some key points regarding regulatory compliance for sustainability in the context of Industry 4.0:

1. Environmental Regulations: Numerous environmental laws that are intended to minimize waste production, cut down on carbon emissions, and preserve natural resources apply to industries. As businesses integrate smart technologies into their operations, they must ensure compliance with these regulations to minimize their environmental footprint (Javaid, Haleem, Singh, Suman, et al., 2022).
2. Data Privacy and Security: Industry 4.0 technology requires the collection and analysis of vast amounts of data from several sources (Klingenberg, Borges, & Antunes Jr, 2021). Adherence to data privacy regulations, such as the General Data Protection Regulation (GDPR) in Europe and similar laws outside are essential in order to protect people's right regarding the privacy concerns and avoiding penalties.
3. Product Safety and Quality Standards: Industries must adhere to product safety and quality standards established by regulatory bodies to ensure that their products meet minimum safety requirements and do not pose risks to consumers or the environment. Compliance with these standards is particularly crucial as manufacturing processes become increasingly automated and interconnected (Ong, Wang, Niyato, & Friedrichs, 2021).

4. Labor Regulations: Sustainability initiatives within Industry 4.0 should also consider labor regulations to ensure fair treatment of workers and adherence to labor standards such as working hours, wages and occupational health and safety. Compliance with these regulations not only promotes social responsibility but also helps maintain a motivated and productive workforce (Islam & AlGeddawy, 2018).
5. Supply Chain Transparency: Transparency in the supply chain is becoming increasingly important for sustainability efforts. Regulatory compliance involves requirements for tracking and disclosing information about the origins of raw materials, labor practices in the supply chain, and environmental impacts associated with production processes.
6. Corporate Governance and Reporting: As part of corporate governance mandates or voluntary sustainability reporting frameworks like SASB (Sustainability Accounting Standards Board) or GRI (Global Reporting Initiative), companies are frequently obliged to report on their sustainability performance and projects. Adherence to these reporting guidelines improves accountability and transparency for stakeholders.
7. Cross-Border Compliance: In an interconnected global economy, companies operating across borders must navigate a complex landscape of regulations and standards in different jurisdictions. Compliance with international agreements and standards related to sustainability, such as the Paris Agreement on climate change, is essential for multinational corporations (Hosseinzadeh, Chen, Shahin, & Bouzary, 2023).

In summary, regulatory compliance is integral to advancing sustainability goals within the framework of Industry 4.0. As a result, by ensuring adherence to environmental, social and governance regulations, companies can mitigate risks, enhance reputation, and contribute to a more sustainable future.

## XII. Collaborative Ecosystems

Industry 4.0 encourages cooperation between interested parties, including government agencies, academia, and industry partners, to address sustainability challenges collectively. These cooperative ecosystems hasten the shift to a more sustainable industrial future by exchanging best practices, technology, and knowledge. In Industry 4.0, collaborative ecosystems are essential for promoting sustainability (Jasiulewicz-Kaczmarek & Gola, 2019). Collaborative ecosystems in Industry 4.0, which is defined by the incorporation of digital technology into supply chains and manufacturing, unite many stakeholders, including communities, governments, enterprises, and academic institutions, to jointly tackle sustainability issues (Mourtzis, Angelopoulos, & Panopoulos, 2022). These ecosystems encourage the exchange of best practices, supplies and information, fostering innovation and efficiency improvements across industries. Here are some key aspects of collaborative ecosystems for sustainability in the context of Industry 4.0:

1. Cross-Sector Collaboration: Collaborative ecosystems bring together players from different sectors, such as technology, manufacturing, energy, and transportation, to leverage their unique expertise and resources for sustainability initiatives (Bianchi & Grippi, 2025). For example, technology companies can develop innovative solutions for energy efficiency in manufacturing processes, while manufacturers can provide real-world testing grounds for these solutions (Sharanya, 2022).
2. Data Sharing and Transparency: Industry 4.0 technologies generate vast amounts of data that can be used to monitor and optimize processes for sustainability. Collaborative ecosystems facilitate data sharing among stakeholders while ensuring privacy and security of data. Transparent access to data enables better decision-making procedures and the identification of areas for improvement processes (Leng et al., 2020).
3. Open Innovation: Collaborative ecosystems foster an environment of open innovation, where participants freely exchange ideas and collaborate on solving common challenges. This approach accelerates the development and adoption of sustainable technologies and practices. Open

innovation platforms and networks enable companies to tap into external expertise and stay at the forefront of sustainability (do Prado, de Souza, & Piekarski, 2025).

4. Supply Chain Integration: Collaboration along the whole supply chain, from suppliers of raw materials to final customers, is frequently necessary for sustainability initiatives. By encouraging visibility, transparency, and cooperation among supply chain participants, collaborative ecosystems can provide easier supply chain integration procedures (Anurag & Johnpaul, 2025). This enables companies to identify and address sustainability risks and opportunities throughout the value chain (Rastogi, Srivastava, Mishra, & Thukral, 2020).
5. Policy and Regulatory Alignment: Collaborative ecosystems provide a platform for stakeholders to engage with policymakers and regulators to shape policies that support sustainability goals. By aligning regulations with industry initiatives, collaborative ecosystems can create an enabling environment for sustainable innovation and investment (Vallim Filho, Farina Moraes, Bhering de Aguiar Vallim, Santos da Silva, & da Silva, 2022).
6. Stakeholder Engagement: For sustainability projects to be successful, stakeholders such as staff members, clients, investors, and local communities must be included. Stakeholders can provide ideas, criticism, and support for sustainability initiatives through the pathways that collaborative ecosystems offer for effective stakeholder interaction.

Overall, collaborative ecosystems play a vital role in advancing sustainability within the framework of Industry 4.0 by promoting collaboration, innovation, and alignment among diverse stakeholders. By working together, stakeholders can provide beneficial social and environmental effects while also unlocking business value and competitiveness in the digital age.

## XIII. Challenges and Opportunities

Combining sustainability in conjunction with industry 4.0 offers opportunity as well as challenges which are crucial for shaping the future of industries and society as a whole.

Challenges:

1. Resource Management: Industry 4.0 technology could end up in higher energy and material consumption, which would be detrimental to sustainability priorities.
2. E-waste: The rapid advancement of technology can lead to increased generation of electronic waste, exacerbating environmental issues if not addressed through proper recycling and disposal methods (Furstenau et al., 2020).
3. Data Privacy and Security: Industry 4.0 relies heavily on data collection and analysis, raising concerns about privacy breaches and data security, which are important considerations for sustainable development (Müller, Kiel, & Voigt, 2018).
4. Skill Gaps: A workforce with the necessary skills to handle automation, data analytics, and cyber-physical systems is necessary for the integration of sophisticated technology. In the age of Industry 4.0, filling talent shortages and offering training opportunities are critical to sustainability (Ciliberto, Szopik-Depczyńska, Tarczyńska-Łuniewska, Ruggieri, & Ioppolo, 2021).
5. Infrastructure Upgrades: Transitioning to Industry 4.0 often requires significant upgrades to existing infrastructure, which can be costly and time-consuming, posing challenges for industries, particularly in developing countries (Sartal, Bellas, Mejías, & García-Collado, 2020).

Opportunities:

1. Efficiency Improvements: IoT, AI, and automation are examples of Industry 4.0 technologies that provide chances to maximize resource use, cut waste, and boost productivity—all of which contribute to sustainability objectives (Javaid, Haleem, Singh, Suman, et al., 2022).

2. Circular Economy: Industry 4.0 enables the implementation of circular economy principles by facilitating product lifecycle tracking, remanufacturing, and recycling through technologies like IoT sensors and blockchain.
3. Predictive Maintenance: By lowering downtime and increasing the lifespan of machinery and equipment, predictive maintenance made possible by IoT-enabled sensors and analytics can support sustainable resource management.
4. Decentralized Energy Systems: By making it easier to integrate localized renewable energy systems—like wind turbines and solar panels—into the current infrastructure, Industry 4.0 encourages the use of clean energy and lowers carbon emissions (Eldrandaly, El Saber, Mohamed, & Abdel-Basset, 2022).
5. Supply Chain Transparency: By guaranteeing ethical sourcing, lowering environmental impact, and providing real-time product tracking from point of origin to point of destination, blockchain and IoT technology could enhance supply chain transparency.
6. Customization and Personalization: Industry 4.0 allows for mass customization and personalized production, reducing overproduction and waste by producing goods according to specific customer demands, thus supporting sustainable consumption patterns (Wolniak & Grebski, 2023).
7. Remote Monitoring and Collaboration: Remote monitoring capabilities enabled by Industry 4.0 technologies facilitate telecommuting and virtual collaboration, reducing the need for physical travel and minimizing carbon footprint associated with commuting (Sivakumar, Dhyankumar, Cherian, Manikandan, & Thejasree, 2023).

While maintaining their competitiveness in the global market, industries can support sustainable growth by tackling these issues and taking use of the opportunities provided by Industry 4.0. However, achieving the aims require a concerted effort from governments, businesses, and society to prioritize sustainability in technological innovation and industrial practices.

## XIV. Conclusion

Industry 4.0 and sustainability together have enormous potential to change industrial systems into more robust, effective, and ecologically friendly operations. In the Fourth Industrial Revolution, companies can attain both economic competitiveness and environmental stewardship by utilizing state-of-the-art technology and encouraging cooperation. By utilizing cutting-edge technologies such as AI, IoT, and data analytics, together with a dedication to sustainable practices, enterprises can improve their competitiveness and productivity while simultaneously reducing their environmental effect and making a beneficial contribution to society. However, for this symbiotic relationship to flourish, stakeholders must collaborate closely, embracing innovation, regulation, and education to navigate the complexities of this transformative journey. By aligning economic prosperity with environmental stewardship, we can pave the way for a future where industries thrive in harmony with our planet, ensuring a legacy of prosperity for generations to come. Through the seamless integration of digital technologies, renewable energy sources, and circular economy principles, we have the opportunity to not only optimize efficiency and productivity but also to minimize environmental impact and foster equitable growth. However, this transition requires collaborative efforts from governments, industries, and individuals alike. By fostering innovation, investing in sustainable solutions and cultivating a culture of responsibility, the full potential of Industry 4.0 can be implemented in order to build a resilient and sustainable living environment.

## XV. Future research work directions

Here are some potential future research directions for the intersection of Industry 4.0 and Sustainable Manufacturing, building upon existing reviews:

1. Integration of Circular Economy Principles: Examine the ways that Industry 4.0 technology might help industrial processes move toward a circular economy. Examine how AI algorithms, IoT sensors, and

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digital twins can optimize resource consumption, facilitate product lifetime management, and encourage recycling and reuse of products.

2. Energy Efficiency Optimization: Further investigate the role of cyber-physical systems (CPS) and AI in optimizing energy consumption across manufacturing operations. Develop novel algorithms and models to dynamically adjust production schedules, equipment settings, and energy sources to minimize environmental impact while maintaining operational efficiency.
3. Sustainable Supply Chain Management: Continue investigating the ways in which Industry 4.0 technology might improve supply chain sustainability. Examine strategies for using blockchain technology to create transparent and traceable supply chains, monitoring suppliers' environmental performance in real time, and applying predictive analytics to reduce sustainability-related supply chain risks.
4. Human-Machine Collaboration for Sustainability: Investigate the socio-technical aspects of human-machine collaboration in sustainable manufacturing contexts. Explore how collaborative robots (cobots), augmented reality, and virtual reality can empower workers to make environmentally conscious decisions and improve overall sustainability performance.
5. Resilience and Adaptability to Environmental Changes: Address the need for manufacturing systems to be resilient and adaptable to environmental changes, such as natural disasters or shifts in regulatory requirements. Research approaches for agile production systems enabled by Industry 4.0 technologies, including reconfigurable manufacturing systems, autonomous maintenance, and decentralized decision-making algorithms.
6. Life Cycle Assessment (LCA) Integration: Explore methods for integrating life cycle assessment (LCA) techniques with Industry 4.0 technologies to provide real-time environmental impact assessments throughout the product lifecycle. Develop interoperable data exchange standards and digital platforms to streamline the collection, analysis, and visualization of LCA data across interconnected manufacturing systems.
7. Policy and Governance Frameworks: Investigate the role of policy and governance frameworks in promoting the adoption of sustainable manufacturing practices enabled by Industry 4.0 technologies. Analyze the effectiveness of existing regulations and incentives, and propose new policy measures to accelerate the transition towards environmentally responsible manufacturing.
8. Cross-Sector Collaboration and Knowledge Sharing: Encourage cooperation between government, business, and academia to promote technology transfer and knowledge exchange in the areas of Industry 4.0 and sustainable manufacturing. Establish interdisciplinary research consortia and collaborative platforms to address complex sustainability challenges and accelerate the development and adoption of innovative solutions.
9. Ethical and Social Implications: Examine the moral and societal ramifications of using Industry 4.0 technology in settings related to sustainable production. Deal with issues including data privacy, job loss, and uneven access to technology. Create frameworks for responsible innovation that put social justice and environmental sustainability first.
10. Validation and Benchmarking: Conduct empirical studies and case analyses to validate the effectiveness and scalability of sustainable manufacturing practices enabled by Industry 4.0 technologies. Develop benchmarking frameworks and key performance indicators (KPIs) to assess the environmental, economic, and social impacts of these practices across different industries and geographic regions.

These future research directions aim to advance knowledge and innovation at the intersection of Industry 4.0 and Sustainable Manufacturing, ultimately contributing to the development of more environmentally sustainable and socially responsible industrial systems.

## References


Al-Ghussain, L., Alrbai, M., Al-Dahidi, S., & Lu, Z. (2024). Integrated assessment of green hydrogen production in California: life cycle Greenhouse gas Emissions, Techno-Economic Feasibility, and resource variability. Energy Conversion and Management, 311, 118514.

Anurag, A., & Johnpaul, M. (2025). Security, Transparency, and Traceability: Role of Blockchain in AI-Powered Supply Chain AI-Powered Business Intelligence for Modern Organizations (pp. 181-206): IGI Global.

Ashima, R., Haleem, A., Bahl, S., Javaid, M., Mahla, S. K., & Singh, S. (2021). Automation and manufacturing of smart materials in Additive Manufacturing technologies using Internet of Things towards the adoption of Industry 4.0. Materials Today: Proceedings, 45, 5081-5088.

Bag, S., & Pretorius, J. H. C. (2022). Relationships between industry 4.0, sustainable manufacturing and circular economy: proposal of a research framework. International Journal of Organizational Analysis, 30(4), 864-898.

Bag, S., Srivastava, G., Cherrafi, A., Ali, A., & Singh, R. K. (2024). Data-driven insights for circular and sustainable food supply chains: An empirical exploration of big data and predictive analytics in enhancing social sustainability performance. Business Strategy and the Environment, 33(2), 1369-1396.

Bahangulu, J. K., & Owusu-Berko, L. (2025). Algorithmic bias, data ethics, and governance: Ensuring fairness, transparency, and compliance in AI-powered business analytics applications. World J Adv Res Rev, 1746-1763.

Beliatis, M. J., Jensen, K., Ellegaard, L., Aagaard, A., & Presser, M. (2021). Next generation industrial IoT digitalization for traceability in metal manufacturing industry: A case study of industry 4.0. Electronics, 10(5), 628.

Bianchi, C., & Grippi, N. (2025). Developing collaborative ecosystem platforms to trigger sustainable “place-based” value creation: a dynamic performance governance approach. International Journal of Productivity and Performance Management, 74(3), 1052-1078.

Bigliardi, B., Bottani, E., & Casella, G. (2020). Enabling technologies, application areas and impact of industry 4.0: a bibliographic analysis. Procedia manufacturing, 42, 322-326.

Camilleri, M. A. (2022). Strategic attributions of corporate social responsibility and environmental management: The business case for doing well by doing good! Sustainable Development, 30(3), 409-422.

Chauhan, S., Singh, R., Gehlot, A., Akram, S. V., Twala, B., & Priyadarshi, N. (2022). Digitalization of supply chain management with industry 4.0 enabling technologies: a sustainable perspective. Processes, 11(1), 96.

Chen, E. (2017). An approach for improving transparency and traceability of industrial supply chain with Blockchain technology.

Ching, N. T., Ghobakhloo, M., Iranmanesh, M., Maroufkhani, P., & Asadi, S. (2022). Industry 4.0 applications for sustainable manufacturing: A systematic literature review and a roadmap to sustainable development. Journal of Cleaner Production, 334, 130133.

Ciliberto, C., Szopik-Depczyńska, K., Tarczyńska-Łuniewska, M., Ruggieri, A., & Ioppolo, G. (2021). Enabling the Circular Economy transition: A sustainable lean manufacturing recipe for Industry 4.0. Business Strategy and the Environment, 30(7), 3255-3272.

Cvetkovski, T., & Tomanovic, V. C. (2024). BENEFITS OF UPSKILLING AND RESKILLING. Economic and Social Development in Period of Global Instability (Book of Proceedings), Special Issue, 241.

Dastres, R., Soori, M., & Asmael, M. (2022). Radio frequency identification (rfid) based wireless manufacturing systems, a review. Independent journal of management & production, 13(1), 258-290.

Davis, J., Edgar, T., Porter, J., Bernaden, J., & Sarli, M. (2012). Smart manufacturing, manufacturing intelligence and demand-dynamic performance. Computers & Chemical Engineering, 47, 145-156.

de Assis Dornelles, J., Ayala, N. F., & Frank, A. G. (2022). Smart Working in Industry 4.0: How digital technologies enhance manufacturing workers' activities. Computers & Industrial Engineering, 163, 107804.

Devaraj, J., Madurai Elavarasan, R., Shafiullah, G., Jamal, T., & Khan, I. (2021). A holistic review on energy forecasting using big data and deep learning models. International journal of energy research, 45(9), 13489-13530.

Dhyani, B. (2021). Predicting Equipment Failure in Manufacturing Plants: An AI-driven Maintenance Strategy. Mathematical Statistician and Engineering Applications, 70(2), 1326-1334.

do Prado, G. F., de Souza, J. T., & Piekarski, C. M. (2025). Sustainable and Innovative: How Can Open Innovation Enhance Sustainability Practices? Sustainability, 17(2), 454.

Dwivedi, D., Mitikiri, S. B., Babu, K. V. S. M., Yemula, P. K., Srinivas, V. L., Chakraborty, P., & Pal, M. (2024). Technological advancements and innovations in enhancing resilience of electrical distribution systems. International Journal of Critical Infrastructure Protection, 100696.

Eisenkopf, A., & Burgdorf, C. (2022). Policy measures and their impact on transport performance, modal split and greenhouse gas emissions in German long-distance passenger transport. Transportation Research Interdisciplinary Perspectives, 14, 100615.

Eldrandaly, K. A., El Saber, N., Mohamed, M., & Abdel-Basset, M. (2022). Sustainable manufacturing evaluation based on enterprise industry 4.0 technologies. Sustainability, 14(12), 7376.

Enyejo, J. O., Fajana, O. P., Jok, I. S., Ihejirika, C. J., Awotiwon, B. O., & Olola, T. M. (2024). Digital Twin Technology, Predictive Analytics, and Sustainable Project Management in Global Supply Chains for Risk Mitigation, Optimization, and Carbon Footprint Reduction through Green Initiatives. International Journal of Innovative Science and Research Technology, 9(11).

Eswaran, U., Eswaran, V., Eswaran, V., & Murali, K. (2024). Human–Robot Collaboration Analyzing the Challenges and Opportunities of Integrating Soft Computing Algorithms in Manufacturing Environments. Evolution and Advances in Computing Technologies for Industry 6.0, 22-51.

Furstenau, L. B., Sott, M. K., Kipper, L. M., Machado, E. L., Lopez-Robles, J. R., Dohan, M. S., . . . Imran, M. A. (2020). Link between sustainability and industry 4.0: trends, challenges and new perspectives. IEEE Access, 8, 140079-140096.

Gawusu, S., Zhang, X., Jamatutu, S. A., Ahmed, A., Amadu, A. A., & Djam Miensah, E. (2022). The dynamics of green supply chain management within the framework of renewable energy. International Journal of Energy Research, 46(2), 684-711.

Ghashghaee, P. (2016). Smart manufacturing: role of Internet of Things in process optimization.

Gligor, D. M., Davis-Sramek, B., Tan, A., Vitale, A., Russo, I., Golgeci, I., & Wan, X. (2022). Utilizing blockchain technology for supply chain transparency: A resource orchestration perspective. Journal of Business Logistics, 43(1), 140-159.

Hegab, H., Shaban, I., Jamil, M., & Khanna, N. (2023). Toward sustainable future: Strategies, indicators, and challenges for implementing sustainable production systems. Sustainable Materials and Technologies, 36, e00617.

Helmrich, A., Markolf, S., Li, R., Carvalhaes, T., Kim, Y., Bondank, E., . . . Chester, M. (2021). Centralization and decentralization for resilient infrastructure and complexity. Environmental Research: Infrastructure and Sustainability, 1(2), 021001.

Hoffmann, M. W., Wildermuth, S., Gitzel, R., Boyaci, A., Gebhardt, J., Kaul, H., . . . Leibfried, T. (2020). Integration of novel sensors and machine learning for predictive maintenance in medium voltage switchgear to enable the energy and mobility revolutions. Sensors, 20(7), 2099.

Hosseinzadeh, A., Chen, F. F., Shahin, M., & Bouzary, H. (2023). A predictive maintenance approach in manufacturing systems via AI-based early failure detection. Manufacturing Letters, 35, 1179-1186.

Islam, M. M., & AlGeddawy, T. (2018). The industrial internet of things models, challenges and opportunities in sustainable manufacturing. Paper presented at the Proceedings of the International Annual Conference of the American Society for Engineering Management.

Jamwal, A., Agrawal, R., Sharma, M., & Giallanza, A. (2021). Industry 4.0 technologies for manufacturing sustainability: A systematic review and future research directions. Applied Sciences, 11(12), 5725.

Jasiulewicz-Kaczmarek, M., & Gola, A. (2019). Maintenance 4.0 technologies for sustainable manufacturing-an overview. IFAC-PapersOnLine, 52(10), 91-96.

Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2022). Enabling flexible manufacturing system (FMS) through the applications of industry 4.0 technologies. Internet of Things and Cyber-Physical Systems, 2, 49-62.

Javaid, M., Haleem, A., Singh, R. P., Suman, R., & Gonzalez, E. S. (2022). Understanding the adoption of Industry 4.0 technologies in improving environmental sustainability. Sustainable operations and computers, 3, 203-217.

Jensen, H. H. (2025). 1st R–Redesign and Reinvent: Laying the Foundation for Circular Success Circular Economy Opportunities and Pathways for Manufacturers: Manufacturing Renewed (pp. 67-102): Springer.

Jiang, Y., Dai, P., Fang, P., Zhong, R. Y., Zhao, X., & Cao, X. (2022). A2-LSTM for predictive maintenance of industrial equipment based on machine learning. Computers & Industrial Engineering, 172, 108560.

Johannsdottir, L., & Davidsdottir, B. (2024). Proposed paradigm shift from shareholders and stakeholders to future successors. Discover Sustainability, 5(1), 194.

Jum'a, L., Ikram, M., & Jabbour, C. J. C. (2024). Towards circular economy: A IoT enabled framework for circular supply chain integration. Computers & Industrial Engineering, 192, 110194.

Jung, S., Kara, L. B., Nie, Z., Simpson, T. W., & Whitefoot, K. S. (2023). Is additive manufacturing an environmentally and economically preferred alternative for mass production? Environmental science & technology, 57(16), 6373-6386.

Karki, B. R., Basnet, S., Xiang, J., Montoya, J., & Porras, J. (2022). Digital maintenance and the functional blocks for sustainable asset maintenance service–A case study. Digital Business, 2(2), 100025.

Khambule, I. (2021). Decentralisation or deconcentration: The case of regional and local economic development in South Africa. Local Economy, 36(1), 22-41.

Khanfar, A. A., Iranmanesh, M., Ghobakhloo, M., Senali, M. G., & Fathi, M. (2021). Applications of blockchain technology in sustainable manufacturing and supply chain management: A systematic review. Sustainability, 13(14), 7870.

Klingenberg, C. O., Borges, M. A. V., & Antunes Jr, J. A. V. (2021). Industry 4.0 as a data-driven paradigm: a systematic literature review on technologies. Journal of manufacturing technology management, 32(3), 570-592.

Kumar Singh, S., Chauhan, A., & Sarkar, B. (2022). Supply chain management of e-waste for end-of-life electronic products with reverse logistics. Mathematics, 11(1), 124.

Lakshmanan, R., Nyamekye, P., Virolainen, V.-M., & Piili, H. (2023). The convergence of lean management and additive manufacturing: Case of manufacturing industries. Cleaner Engineering and Technology, 13, 100620.

Leng, J., Ruan, G., Jiang, P., Xu, K., Liu, Q., Zhou, X., & Liu, C. (2020). Blockchain-empowered sustainable manufacturing and product lifecycle management in industry 4.0: A survey. Renewable and sustainable energy reviews, 132, 110112.

Lopes, J. D., Estevão, J., & Toth-Peter, A. (2023). Industry 4.0, multinationals, and sustainable development: A bibliometric analysis. Journal of Cleaner Production, 413, 137381.

Lu, Y., & Li, S. (2023). Green transportation model in logistics considering the carbon emissions costs based on improved grey wolf algorithm. Sustainability, 15(14), 11090.

Maiurova, A., Kurniawan, T. A., Kustikova, M., Bykovskaia, E., Othman, M. H. D., Singh, D., & Goh, H. H. (2022). Promoting digital transformation in waste collection service and waste recycling in Moscow (Russia): Applying a circular economy paradigm to mitigate climate change impacts on the environment. Journal of Cleaner Production, 354, 131604.

Mastrocinque, E., Ramírez, F. J., Honrubia-Escribano, A., & Pham, D. T. (2022). Industry 4.0 enabling sustainable supply chain development in the renewable energy sector: A multi-criteria intelligent approach. Technological Forecasting and Social Change, 182, 121813.

Matsunaga, F., Zytkowski, V., Valle, P., & Deschamps, F. (2022). Optimization of energy efficiency in smart manufacturing through the application of cyber–physical systems and industry 4.0 technologies. Journal of Energy Resources Technology, 144(10), 102104.

Michalos, G., Makris, S., Tsarouchi, P., Guasch, T., Kontovrakis, D., & Chryssolouris, G. (2015). Design considerations for safe human-robot collaborative workplaces. Procedia CIrP, 37, 248-253.

Molęda, M., Małysiak-Mrozek, B., Ding, W., Sunderam, V., & Mrozek, D. (2023). From corrective to predictive maintenance—A review of maintenance approaches for the power industry. Sensors, 23(13), 5970.

Mourtzis, D., Angelopoulos, J., & Panopoulos, N. (2022). A Literature Review of the Challenges and Opportunities of the Transition from Industry 4.0 to Society 5.0. Energies, 15(17), 6276.

Mtetwa, C. (2024). Reverse Logistics and Waste Reduction Alternatives Contemporary Solutions for Sustainable Transportation Practices (pp. 345-373): IGI Global.

Mubarik, M., Raja Mohd Rasi, R. Z., Mubarak, M. F., & Ashraf, R. (2021). Impact of blockchain technology on green supply chain practices: evidence from emerging economy. Management of Environmental Quality: An International Journal, 32(5), 1023-1039.

Müller, J. M., Kiel, D., & Voigt, K.-I. (2018). What drives the implementation of Industry 4.0? The role of opportunities and challenges in the context of sustainability. Sustainability, 10(1), 247.

Ngu, H. J., Lee, M. D., & Osman, M. S. B. (2020). Review on current challenges and future opportunities in Malaysia sustainable manufacturing: Remanufacturing industries. Journal of Cleaner Production, 273, 123071.

Nguyen, M.-T., & Batel, S. (2021). A critical framework to develop human-centric positive energy districts: towards justice, inclusion, and well-being. Frontiers in Sustainable Cities, 3, 691236.

Nweje, U., & Taiwo, M. (2025). Supply chain management: Balancing efficiency and environmental responsibility. World Journal of Advanced Research and Reviews, 25(1), 1547-1564.

Ong, K. S. H., Wang, W., Niyato, D., & Friedrichs, T. (2021). Deep-reinforcement-learning-based predictive maintenance model for effective resource management in industrial IoT. IEEE Internet of Things Journal, 9(7), 5173-5188.

Paolanti, M., Romeo, L., Felicetti, A., Mancini, A., Frontoni, E., & Loncarski, J. (2018). Machine learning approach for predictive maintenance in industry 4.0. Paper presented at the 2018 14th IEEE/ASME International Conference on Mechatronic and Embedded Systems and Applications (MESA).

Park, A., & Li, H. (2021). The effect of blockchain technology on supply chain sustainability performances. Sustainability, 13(4), 1726.

Patel, K. R. (2023). Enhancing global supply chain resilience: Effective strategies for mitigating disruptions in an interconnected world. BULLET: Jurnal Multidisiplin Ilmu, 2(1), 257-264.

Patil, D. (2024). Artificial intelligence-driven predictive maintenance in manufacturing: enhancing operational efficiency, minimizing downtime, and optimizing resource utilization. Minimizing Downtime, And Optimizing Resource Utilization (December 11, 2024).

Pech, M., Vrchota, J., & Bednář, J. (2021). Predictive maintenance and intelligent sensors in smart factory. Sensors, 21(4), 1470.

Prashar, G., Vasudev, H., & Bhuddhi, D. (2023). Additive manufacturing: expanding 3D printing horizon in industry 4.0. International Journal on Interactive Design and Manufacturing (IJIDeM), 17(5), 2221-2235.

Rastogi, V., Srivastava, S., Mishra, M., & Thukral, R. (2020). Predictive maintenance for sme in industry 4.0. Paper presented at the 2020 Global Smart Industry Conference (GloSIC).

Ridzi, F., & Prior, T. (2023). Community leadership through conversations and coordination: The role of local surveys in community foundation run community indicators projects. International Journal of Community Well-Being, 6(2), 127-150.

Sanchez, D. O. M. (2019). Sustainable development challenges and risks of Industry 4.0: A literature review. 2019 Global IoT Summit (GIoTS), 1-6.

Sartal, A., Bellas, R., Mejías, A. M., & García-Collado, A. (2020). The sustainable manufacturing concept, evolution and opportunities within Industry 4.0: A literature review. Advances in Mechanical Engineering, 12(5), 1687814020925232.

Shabur, M. A. (2024). A comprehensive review on the impact of Industry 4.0 on the development of a sustainable environment. Discover Sustainability, 5(1), 97.

Sharanya, S. (2022). A cyber physical system framework for industrial predictive maintenance using machine learning Real-Time Applications of Machine Learning in Cyber-Physical Systems (pp. 241-269): IGI Global.

Singh, A., Madaan, G., Hr, S., & Kumar, A. (2023). Smart manufacturing systems: a futuristics roadmap towards application of industry 4.0 technologies. International Journal of Computer Integrated Manufacturing, 36(3), 411-428.

Singh, B., & Kaunert, C. (2024). Adventure in High Altitude of Mountainous Topographies and Health Impacts: Lensing Tourism Sustainability via Reducing Ecological and Sociocultural Footprint and Health Emergency and Medical Assistance Management Navigating Natural Hazards in Mountainous Topographies: Exploring the Challenges and Opportunities of Living (pp. 281-303): Springer.

Singh, B., & Nayyar, A. (2025). Exploring diverse use cases of digital twins projecting digital transformation: Unlocking potential, addressing challenges and viable solutions Digital Twins for Smart Cities and Villages (pp. 631-655): Elsevier.

Sivakumar, K., Dhyankumar, C. T., Cherian, T. M., Manikandan, N., & Thejasree, P. (2023). Requirements for the Adoption of Industry 4.0 in the Sustainable Manufacturing Supply Chain Industry 4.0 Technologies: Sustainable Manufacturing Supply Chains: Volume II-Methods for transition and trends (pp. 185-201): Springer.

Sohaib, M., Mushtaq, S., & Uddin, J. (2021). Deep learning for data-driven predictive maintenance Vision, Sensing and Analytics: Integrative Approaches (pp. 71-95): Springer.

Soori, M. (2019). Virtual product development: GRIN Verlag.

Soori, M. (2023a). Advanced Composite Materials and Structures. Journal of Materials and Engineering Structures.

Soori, M. (2023b). Deformation error compensation in 5-Axis milling operations of turbine blades. Journal of the Brazilian Society of Mechanical Sciences and Engineering, 45(6), 289. doi:10.1007/s40430-023-04230-w

Soori, M., & Arezoo, B. (2020). Virtual machining systems for CNC milling and turning machine tools: a review. International Journal of Engineering and Future Technology, 18(1), 56-104.

Soori, M., & Arezoo, B. (2022a). Cutting Tool Wear Prediction in Machining Operations, A Review. Journal of New Technology and Materials, 12(2), 15-26.

Soori, M., & Arezoo, B. (2022b). A Review in Machining-Induced Residual Stress. Journal of New Technology and Materials, 12(1), 64-83.

Soori, M., & Arezoo, B. (2023a). Cutting tool wear minimization in drilling operations of titanium alloy Ti-6Al-4V. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 13506501231158259.

Soori, M., & Arezoo, B. (2023b). Dimensional, geometrical, thermal and tool deflection errors compensation in 5-Axis CNC milling operations. Australian Journal of Mechanical Engineering, 1-15.

Soori, M., & Arezoo, B. (2023c). Effect of Cutting Parameters on Tool Life and Cutting Temperature in Milling of AISI 1038 Carbon Steel. Journal of New Technology and Materials.

Soori, M., & Arezoo, B. (2023d). The effects of coolant on the cutting temperature, surface roughness and tool wear in turning operations of Ti6Al4V alloy. Mechanics Based Design of Structures and Machines, 1-23. doi:10.1080/15397734.2023.2200832

Soori, M., & Arezoo, B. (2023e). Minimization of surface roughness and residual stress in abrasive water jet cutting of titanium alloy Ti6Al4V. Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering, 09544089231157972.

Soori, M., & Arezoo, B. (2023f). Modification of CNC Machine Tool Operations and Structures Using Finite Element Methods, A Review. Jordan Journal of Mechanical and Industrial Engineering.

Soori, M., Arezoo, B., & Dastres, R. (2023a). Artificial Intelligence, Machine Learning and Deep Learning in Advanced Robotics, A Review. Cognitive Robotics, 3, 54-70.

Soori, M., Arezoo, B., & Dastres, R. (2023b). Artificial Neural Networks in Supply Chain Management, A Review. Journal of Economy and Technology.

Soori, M., Arezoo, B., & Dastres, R. (2023c). Internet of things for smart factories in industry 4.0, a review. Internet of Things and Cyber-Physical Systems.

Soori, M., Arezoo, B., & Dastres, R. (2023d). Machine Learning and Artificial Intelligence in CNC Machine Tools, A Review. Sustainable Manufacturing and Service Economics, 100009. doi:10.1016/j.smse.2023.100009

Soori, M., Arezoo, B., & Dastres, R. (2023e). Optimization of Energy Consumption in Industrial Robots, A Review. Cognitive Robotics. doi:10.1016/j.cogr.2023.05.003

Soori, M., Arezoo, B., & Dastres, R. (2023f). Virtual manufacturing in industry 4.0: A review. Data Science and Management.

Soori, M., Arezoo, B., & Habibi, M. (2013). Dimensional and geometrical errors of three-axis CNC milling machines in a virtual machining system. Computer-Aided Design, 45(11), 1306-1313.

Soori, M., Arezoo, B., & Habibi, M. (2014). Virtual machining considering dimensional, geometrical and tool deflection errors in three-axis CNC milling machines. Journal of Manufacturing Systems, 33(4), 498-507.

Soori, M., Arezoo, B., & Habibi, M. (2016). Tool deflection error of three-axis computer numerical control milling machines, monitoring and minimizing by a virtual machining system. Journal of Manufacturing Science and Engineering, 138(8), 081005.

Soori, M., Arezoo, B., & Habibi, M. (2017). Accuracy analysis of tool deflection error modelling in prediction of milled surfaces by a virtual machining system. International Journal of Computer Applications in Technology, 55(4), 308-321.

Soori, M., & Asmael, M. (2021a). Classification of research and applications of the computer aided process planning in manufacturing systems. Independent Journal of Management & Production, 12(5), 1250-1281.

Soori, M., & Asmael, M. (2021b). Cutting temperatures in milling operations of difficult-to-cut materials. Journal of New Technology and Materials, 11(1), 47-56.

Soori, M., & Asmael, M. (2021c). Minimization of deflection error in five axis milling of impeller blades. Facta Universitatis, series: Mechanical Engineering, 21(2), 175-190.

Soori, M., & Asmael, M. (2021d). Virtual Minimization of Residual Stress and Deflection Error in Five-Axis Milling of Turbine Blades. Strojniski Vestnik/Journal of Mechanical Engineering, 67(5), 235-244.

Soori, M., & Asmael, M. (2022). A Review of the Recent Development in Machining Parameter Optimization. Jordan Journal of Mechanical & Industrial Engineering, 16(2), 205-223.

Soori, M., Asmael, M., Khan, A., & Farouk, N. (2021). Minimization of surface roughness in 5-axis milling of turbine blades. Mechanics Based Design of Structures and Machines, 51(9), 1-18.

Soori, M., Asmael, M., & Solyalı, D. (2020). Recent Development in Friction Stir Welding Process: A Review. SAE International Journal of Materials and Manufacturing(5), 18.

Sudusinghe, J. I., & Seuring, S. (2022). Supply chain collaboration and sustainability performance in circular economy: A systematic literature review. International Journal of Production Economics, 245, 108402.

Trstenjak, M., Opetuk, T., Cajner, H., & Tosanovic, N. (2020). Process planning in Industry 4.0—Current state, potential and management of transformation. Sustainability, 12(15), 5878.

Tyagi, A. K., Bhatt, P., Chidambaram, N., & Kumari, S. (2024). Artificial intelligence empowered smart manufacturing for modern society: a review. Artificial Intelligence-Enabled Digital Twin for Smart Manufacturing, 55-83.

Vacchi, M., Siligardi, C., Cedillo-González, E. I., Ferrari, A. M., & Settembre-Blundo, D. (2021). Industry 4.0 and smart data as enablers of the circular economy in manufacturing: Product re-engineering with circular eco-design. Sustainability, 13(18), 10366.

Vallim Filho, A. R. d. A., Farina Moraes, D., Bhering de Aguiar Vallim, M. V., Santos da Silva, L., & da Silva, L. A. (2022). A machine learning modeling framework for predictive maintenance based on equipment load cycle: an application in a real world case. Energies, 15(10), 3724.

Varghese, A., Ande, J., Mahadasa, R., Gutlapalli, S. S., & Surarapu, P. (2023). Investigation of fault diagnosis and prognostics techniques for predictive maintenance in industrial machinery. Engineering International, 11(1), 9-26.

Wolniak, R., & Grebski, W. (2023). The customization and personalization of product in Industry 4.0. Sci. Pap. Silesian Univ. Technol. Organ. Manag. Ser, 2023, 180.

Yan, H., Wan, J., Zhang, C., Tang, S., Hua, Q., & Wang, Z. (2018). Industrial big data analytics for prediction of remaining useful life based on deep learning. IEEE Access, 6, 17190-17197.

Yin, L., Luo, J., & Luo, H. (2018). Tasks scheduling and resource allocation in fog computing based on containers for smart manufacturing. IEEE transactions on Industrial informatics, 14(10), 4712-4721.

Zhao, W., Chen, H., & Bulis, A. (2025). How are Industry 4.0 technologies transforming a sustainable society across industries? Digital Transformation and Society, 4(3), 363-380.

Zheng, P., Wang, H., Sang, Z., Zhong, R. Y., Liu, Y., Liu, C., . . . Xu, X. (2018). Smart manufacturing systems for Industry 4.0: Conceptual framework, scenarios, and future perspectives. Frontiers of Mechanical Engineering, 13, 137-150.

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AUTHORS

**Mohsen Soori** is with the mechanical engineering department of Amirkabir University of Technology, Iran (e-mail: m.soori@aut.ac.ir).

ORCID ID: 0000-0002-4358-7513

**Behrooz Arezoo** is with the mechanical engineering department of Amirkabir University of Technology, Iran (e-mail: arezoo@aut.ac.ir).

ORCID ID: 0000-0002-3054-4696

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**Pregled trajnostne proizvodnje v industriji 4.0 z umetno inteligenco in internetom stvari**

**Izvleček** – Umetna inteligenca (v nadaljevanju: AI), internet stvari (v nadaljevanju: IoT) in analiza podatkov se uporabljajo za zagotavljanje spremljanja in optimizacije izkoriščanja virov v realnem času, v dobi Industrije 4.0. Posledično se tudi zmanjša količina odpadkov in izboljša učinkovitost virov, kar zmanjša vpliv na okolje in podpira cilje trajnosti. Zaradi vse večje zaskrbljenosti glede okoljskih vprašanj je trajnost postala temeljna predpostavka sodobnih industrijskih sistemov. Da bi predstavili napredne modele in metodologije uporabe AI in IoT za izboljšanje trajnosti proizvodnje delov v industriji 4.0, je v študiji predstavljen pregled najnovejših razvojnih dosežkov. Analizira uporabo AI, IoT in analitike podatkov v smislu optimizacije virov in odločanja v zvezi s trajnostnimi vprašanji proizvodnih postopkov. Ta študija preučuje, kako se lahko Industrija 4.0 uporabi za trajnostno proizvodnjo, z izboljšanjem učinkovitosti virov, vključevanjem obnovljivih virov energije, omogočanjem praks krožnega gospodarstva in spodbujanjem preglednosti oskrbovalne verige. Študija združuje podatke iz nedavnih raziskovalnih del, da bi pojasnila prispevek pametne proizvodnje, prediktivnega vzdrževanja, virtualnega obdelovanja in upravljanja oskrbovalne verige, podprtega z veriženjem blokov, v smislu zmanjševanja odpadkov, porabe energije in vpliva na okolje v napredni proizvodnji. Članek obravnava tudi uporabo tehnologij umetne inteligence in interneta stvari v smislu izboljšanja sledljivosti, preglednosti in učinkovitosti v procesih upravljanja oskrbovalne verige. Predstavljene in obravnavane so tudi uporabe decentralizirane proizvodnje, človeško usmerjenega oblikovanja in sodelovalnih industrijskih ekosistemov. Poleg tega študija obravnava tudi ključne izzive, med katerimi so naraščanje količine elektronskih odpadkov, grožnje za zasebnost podatkov, pomanjkanje kadrov in potreba po podpornih zakonodajnih okvirih in odpornih digitalnih infrastrukturah. Poleg tega so predstavljene in obravnavane nove ideje, ki ponujajo potencialne smernice za prihodnje raziskave na področju umetne inteligence in aplikacij interneta stvari za doseganje trajnosti v okviru paradigme industrije 4.0. Študija tako ponuja praktične vpoglede in priporočila, ki raziskovalcem, zainteresiranim stranem iz industrije in zakonodajalcem omogočajo analizo in razvoj strategij trajnosti v industrijskem kontekstu v dobi industrije 4.0.

**Ključne besede** – Industrija 4.0, trajnostna proizvodnja, umetna inteligenca, internet stvari