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Industry 5.0: A Human-Centric Paradigm for Sustainable and Resilient Industrial Transformation

Endüstri 5.0: Sürdürülebilir ve Dirençli Endüstriyel Dönüşüm için İnsan Merkezli Bir Paradigma

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ÖZ

Endüstri 5.0'ın ortaya çıkışı, Endüstri 4.0'ın otomasyon odaklı çerçevesinden daha insan merkezli, sürdürülebilir ve dirençli bir endüstriyel geleceğe doğru bir paradigma değişimini temsil etmektedir. Bu çalışma, Endüstri 5.0'ın kavramsal gelişimini, teknolojik temellerini ve imalat, sağlık, tarım, lojistik ve tedarik zinciri sistemlerindeki çok boyutlu uygulamalarını araştırmaktadır. Endüstri 5.0, işbirliğine dayalı insan-makine etkileşimini, etik hususları ve çevresel sorumluluğu vurgulayarak, yalnızca operasyonel verimliliği artırmakla kalmayıp aynı zamanda insan refahına ve ekolojik idareye öncelik veren üretim modellerini yeniden tanımlamayı amaçlamaktadır. Güncel literatür, politika çerçeveleri ve sektöre özgü vaka çalışmalarından yararlanan bu makale, yapay zeka, nesnelerin interneti, robotik ve dijital ikizler gibi ileri teknolojilerin kitlesel kişiselleştirme, döngüsel ekonomi ve karbon-nötr üretimin gerçekleştirilmesine nasıl katkıda bulunduğunu analiz etmektedir. Araştırma ayrıca, veri gizliliği, altyapı uyumluluğu ve etik sonuçlar gibi temel zorlukları tanımlarken, inovasyon, kapsayıcı istihdam ve sürdürülebilir kalkınma için ortaya çıkan fırsatları vurgulamaktadır. Bulgular, Endüstri 5.0'ın endüstriyel ilerlemeyi daha geniş toplumsal ve çevresel hedeflerle uyumlu hale getirme konusundaki dönüştürücü potansiyelinin altını çizmektedir.

Anahtar Kelimeler: Endüstri 5.0, İnsan-Makine İşbirliği, Sürdürülebilir Üretim, Akıllı Teknolojiler, Döngüsel Ekonomi

ABSTRACT

The emergence of Industry 5.0 represents a paradigm shift from the automation-focused framework of Industry 4.0 toward a more human-centric, sustainable, and resilient industrial future. This study explores the conceptual evolution, technological foundations, and multidimensional applications of Industry 5.0 across manufacturing, healthcare, agriculture, logistics, and supply chain systems. By emphasizing collaborative human-machine interaction, ethical considerations, and environmental responsibility, Industry 5.0 seeks to redefine production models that not only enhance operational efficiency but also prioritize human well-being and ecological stewardship. Drawing on recent literature, policy frameworks, and sector-specific case studies, this paper analyzes how advanced Technologies such as artificial intelligence, the Internet of Things, robotics, and digital twins contribute to the realization of mass customization, circular economy, and carbon-neutral production. Furthermore, the research identifies key challenges including data privacy, infrastructure adaptability, and ethical implications, while highlighting emerging opportunities for innovation, inclusive employment, and sustainable development. The findings underscore the transformative potential of Industry 5.0 in aligning industrial advancement with broader societal and environmental goals.

Keywords: Industry 5.0, Human-Machine Collaboration, Sustainable Manufacturing, Smart Technologies, Circular Economy

ÖNEÇIKANLAR/HİGHLİGHTS

Industry 5.0 introduces a transformative framework that integrates human-centric values with sustainable and resilient industrial practices. Advanced technologies such as AI, digital twins, and collaborative robotics enable flexible production systems aligned with environmental responsibility and societal well-being.

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1. Introduction

The first quarter of the twenty-first century has been marked by rapid technological innovation and profound changes in industrial production systems. Industry 5.0, regarded as the most recent phase in this evolution, not only incorporates cutting-edge technological advancements but also introduces a fundamentally human-centric approach. While Industry 4.0 emphasized digitalization, automation, and the Internet of Things (IoT) in production processes, Industry 5.0 integrates human capabilities into these systems to establish more meaningful, adaptable, and sustainable models of production (Nalbant & Aydın, 2025).

The policy document published by the European Commission in 2021 laid the conceptual foundation for Industry 5.0, emphasizing that this new industrial paradigm extends beyond economic efficiency to encompass human well-being, environmental sustainability, and societal resilience (Yetkin & Coşkun, 2021). In this context, Industry 5.0 does not merely promote the increased use of digital technologies; it redefines their application by embedding human-machine collaboration, ethical considerations, and ecological responsibility at the core of industrial innovation. Characterized by its human-centered philosophy, Industry 5.0 represents a significant departure from previous industrial revolutions. It aims to merge advanced technologies with human creativity and intuition, thereby fostering collaborative production environments that are flexible, personalized, and aligned with sustainability goals.

Recent academic studies define Industry 5.0 from various perspectives. For instance, Nahavandi (2019) defines the concept as "a production paradigm based on the synergistic collaboration between humans and robots," while George et al. (2023) describe Industry 5.0 as "an intelligent manufacturing ecosystem sensitive to ethical values, environmental responsibility, and individual needs." The common denominator in these definitions is the notion that technological advancement should be strategically optimized for the benefit of humanity.

Although relatively new, Industry 5.0 has rapidly gained momentum across the globe. It builds upon the technological pillars of Industry 4.0 while incorporating social dimensions such as workplace flexibility, opportunities for professional development, and a greater emphasis on work-life balance. Introduced by the European Commission in 2021, this approach seeks to establish a sustainable, human-centered, and resilient industrial framework across Europe (Cotta et al., 2021). By offering transformative potential, Industry 5.0 enhances the resilience and adaptability of manufacturing systems and global supply chains (Ahmed et al., 2023).

Beyond its sustainability and resilience agenda, Industry 5.0 paradigm places strong emphasis on worker well-being. It promotes the development of technologies, methodologies, and organizational models that cultivate an engaging, rewarding, and supportive working environment tailored to human needs (Orso et al., 2022).

The existing literature includes numerous studies examining the implications of Industry 5.0 for sustainable development. A recent bibliometric study by Yiğit and Engin (2025) evaluates the sustainability potential of Industry 5.0 by analyzing influential publications, citation patterns, and prevailing research themes. Within the field of supply chain management, Teoman (2024) presents a strategic and technological framework for integrating human-centered design into supply chains aligned with the principles of Industry 5.0. This study underscores the need for new strategic and technological configurations to ensure effective implementation.

Applications of Industry 5.0 are expanding rapidly across various sectors, including manufacturing, healthcare, agriculture, and logistics. Hybrid operational models merging artificial intelligence, big data, cloud computing, and advanced robotics with human ingenuity are becoming increasingly prevalent (Maddikunta, 2022). Key features of Industry 5.0 include human-robot collaboration, mass customization, and sustainable manufacturing. These features allow for optimized production processes, increased quality, and responsiveness to individualized customer demands. From a sustainability standpoint, environmentally responsible production practices and efficient resource utilization are prioritized. Ultimately, Industry 5.0 envisions a future in which technology and human skills operate in harmony. As such, it presents both opportunities and imperatives for businesses, governments, and society at large to engage with this transformative shift and contribute to a more sustainable and inclusive industrial future.

2. The Concept of Industry 5.0

Industry 5.0 is a new industrial paradigm in which technological advancements integrate with human-centered values. Unlike the machine and system-focused digitization processes of Industry 4.0, Industry 5.0 makes human, societal, and environmental dimensions an inseparable part of production processes. This approach aims to align human-machine collaboration not only in terms of productivity but also in harmony with ethical, sustainable, and personalized production models (Nahavandi, 2019).

The conceptual development of *Industry 5.0* has emerged as a response to the limitations and unintended consequences of the technology-centric approach of *Industry 4.0*. Although Industry 4.0 brought unprecedented levels of automation, digital integration, and operational efficiency, it also revealed critical challenges such as the marginalization of human roles, deepening environmental degradation, and systemic fragilities—particularly exposed during global crises like the COVID-19 pandemic (Zhang et al., 2023). These challenges underscored the need for a more resilient, adaptable, and socially responsible industrial model. In this context, the European Commission's 2021 framework for Industry 5.0 introduced a forward-looking paradigm centered on three foundational pillars: human-centricity, sustainability, and resilience.

Industry 5.0 reimagines industrial production as a collaborative ecosystem in which humans and machines work synergistically to enhance not only productivity but also the

quality and meaning of work. Unlike its predecessor, this new paradigm does not aim to replace human input but rather to elevate it—particularly in areas where human creativity, intuition, and ethical judgment are irreplaceable. Collaborative robots (cobots), artificial intelligence, and intelligent automation systems are deployed not as substitutes for human labor, but as tools to augment human potential. In this sense, executive leadership within manufacturing firms assumes a pivotal role in designing production systems that integrate real-time data analysis, performance monitoring, and seamless operational coordination (Adel, 2022).

The increasing consumer demand for personalized and value-driven products further reinforces the necessity of human involvement in advanced manufacturing. This demand requires not only flexible automation but also innovative product development driven by human creativity. As Industry 5.0 evolves, it becomes evident that human skills are more vital than ever in steering intelligent systems, configuring ethical frameworks, and ensuring social responsiveness in technological adoption.

The transformation of manufacturing paradigms across five industrial revolutions illustrates this evolution. According to Lu et al. (2022), the First Industrial Revolution was defined by craft production—producing handmade, personalized goods with high cost and low scalability. The Second Industrial Revolution introduced mass production through standardized assembly lines, enhancing output but sacrificing customization. The Third Industrial Revolution brought computer-integrated manufacturing and flexible systems, enabling mass customization. Industry 4.0 added real-time connectivity and automation, allowing for *mass personalization*—highly customized products produced with the speed and efficiency of mass production. Despite these advances, challenges such as self-organizing autonomy and adaptive flexibility remain unresolved, especially in dynamic markets. Here, Industry 5.0 extends the trajectory by reintegrating the human element as a critical component in intelligent decision-making and innovation processes (Lu et al., 2022).

The conceptual and operational framework of Industry 5.0 is structured around four interrelated pillars human-machine interaction, sustainability, resilience, and personalization which collectively define its implementation in industrial systems. At its core, Industry 5.0 emphasizes the synergistic integration of robots, artificial intelligence, and digital technologies with human operators, leveraging uniquely human attributes such as emotional intelligence, critical judgment, creativity, and adaptability to enhance collaborative tasks (Nguyen & Tran, 2023). Sustainability is embedded as a foundational principle, guiding the development of environmentally responsible technologies and promoting practices such as green manufacturing, renewable energy utilization, circular economy models, and resource-efficient production (Narkhede et al., 2025). In parallel, resilience is prioritized to ensure that industrial systems can withstand and adapt to external shocks, including supply chain disruptions and global crises. Key technologies such as digital twins, scenario-based simulations, and reconfigurable production

infrastructures support this adaptive capacity (Shishodia et al., 2023). Recent studies further emphasize the role of agentic AI-based supply chain automation frameworks like SustAI-SCM in enhancing resilience by dynamically optimizing procurement, logistics, and inventory operations (Aylak, 2025). Moreover, the integration of digital trends such as autonomous logistics, IoT, and cloud-based logistics platforms has been shown to strengthen the agility and responsiveness of supply networks (Ivanov et al., 2022). Sustainability-driven strategies also foster the creation of resilient partnerships across the supply chain, enabling organizations to better navigate environmental and operational uncertainties (Aylak, 2022). Finally, Industry 5.0 advances the paradigm of mass customization by enabling firms to respond precisely to individualized customer demands through personalized product design, flexible manufacturing processes, and intelligent service systems (Wang et al., 2024). Collectively, these components reflect a holistic and forward-thinking vision for a human-centric, sustainable, and agile industrial future (Figure 1).

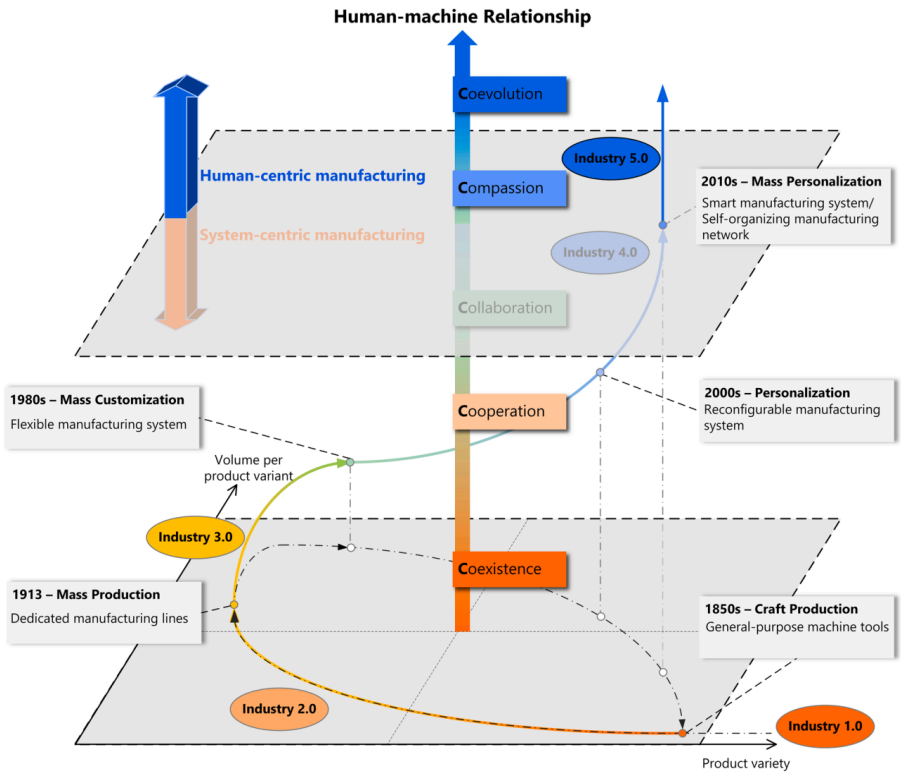

Figure 1: Evolution of Human-Machine Relationships in Manufacturing

This diagram illustrates the progressive shifts in the human-machine relationship over the course of the five Industrial Revolutions, showcasing the transition towards human-centric manufacturing (Lu et al., 2022).

This integrated approach illustrates that Industry 5.0 is not merely an extension of digitalization, but a profound reorientation of industrial priorities placing human value, ecological stewardship, and adaptive capability at the center of innovation.

3. Industrial Applications of Industry 5.0

The sectoral applications of *Industry 5.0* are rooted in the seamless integration of advanced technologies with human capabilities, enabling production systems to become more flexible, intelligent, and adaptive. This transformation is particularly evident in sectors such as manufacturing, healthcare, agriculture, and logistics, where the collaboration between humans and machines, AI-driven systems, and sustainable technologies is reshaping operational paradigms.

Building upon the technological infrastructure established by *Industry 4.0*, Industry 5.0 introduces a paradigm shift that emphasizes human-centricity, resilience, and sustainability at its core (Kasinathan et al., 2022). While Industry 4.0 primarily focuses on leveraging digital technologies to improve efficiency and address manufacturing-specific challenges, Industry 5.0 adopts a more holistic perspective prioritizing not only customer-centric production but also the overall well-being and empowerment of human workers (Barata & Kayser, 2023). In this context, previous studies have illustrated the pivotal role of Industry 4.0 technologies in creating a smart manufacturing ecosystem (Çetinkaya et al., 2019), particularly in fields such as digital agriculture, where the Internet of Things (IoT), autonomous robots, and cloud computing have significantly improved productivity and sustainability (Duman & Özsoy, 2023).

A cornerstone of Industry 5.0 is the deployment of cobots that are designed to assist human operators while minimizing occupational risks. These robots are capable of perceiving, understanding, and adapting to human behaviors, intentions, and expectations. The objective is not merely to automate tasks but to enhance the efficiency and quality of work by supporting human actions through learning and adaptation.

Furthermore, Industry 5.0 signifies a deeper and more pervasive integration of artificial intelligence (AI) into industrial processes and daily life. It leverages a wide range of enabling Technologies including the Internet of Things (IoT), AI, robotics, and augmented reality to foster intelligent, adaptive, and human-friendly environments. These environments are designed to enhance not only operational performance but also worker satisfaction and quality of life (Akundi et al., 2022).

The comparative distinction between Industry 4.0 and Industry 5.0 can be illustrated through several critical dimensions, as shown in Table 1. This comparison highlights the evolution from automation-centered design toward a collaborative, sustainable, and human-centered industrial future.

Table 1: *Comparison of Industry 4.0 and Industry 5.0*

Aspect	Industry 4.0	Industry 5.0
Job Focus	Less emphasis on skilled labor; automation-driven	Emphasizes skilled labor; fosters collaboration between humans and machines

Production Approach	Mass production via robotic automation	Mass customization supported by human-robot collaboration
Role of Robots	Robots primarily responsible for large-scale automation	Cobots work interactively with humans to complement their skills
Customer Focus	Limited personalization; standard product offerings	Strong emphasis on customized solutions and customer satisfaction
Technology Focus	Focus on Cyber-Physical Systems (CPS) and connectivity	Builds on CPS with a focus on intelligent human-machine collaboration
Environmental View	Limited integration of environmental concerns	Promotes sustainability, eco-friendly practices, and circular economy models
Decision-Making	Minimal use of predictive modeling	Advanced predictive analytics and decision intelligence integrated with human insight
Automation	Fully automated systems with minimal human input	Automation enhanced by real-time data and expert human oversight

This table compares the key aspects of Industry 4.0 and Industry 5.0, highlighting the differences in job focus, production approach, the role of robots, customer and environmental concerns, decision-making, and automation strategies. (Adapted from Maddikunta, 2022)

3.1. Manufacturing Sector: Collaborative Robots and Smart Factories

One of the most prominent applications of Industry 5.0 is in the manufacturing industry. The foundation of this transformation is cobots, which work alongside human operators. Cobots take over routine and repetitive tasks, allowing human workers to focus on cognitive skills such as creativity and problem-solving (Liu et al., 2024). As a result, the flexibility and customization capabilities in production lines are enhanced.

Within Industry 5.0, cobot systems developed by companies like KUKA and Universal Robots are widely used in the automotive and electronics sectors. These systems, particularly in automotive assembly lines, increase human-robot collaboration, enabling flexible production processes (Borboni et al., 2023). In Turkey, companies such as Vestel and Ford Otosan are pioneers in this transformation, investing in production systems that integrate human-robot collaboration. For example, Ford Otosan aims to enhance production efficiency by integrating robotic technologies into its production lines (Yetkin & Ulutaş, 2022).

3.2. Healthcare Sector: Personalized Medicine and Robotic Support

In healthcare, Industry 5.0 supports solutions tailored to individual health needs. Technologies such as robotic surgical systems, AI-based diagnostic algorithms, and 3D bioprinting enable patient-specific treatment approaches (Garg, 2022).

The Da Vinci Surgical Robot integrates with human surgeons to perform complex surgeries with higher precision, while AI systems suggest personalized treatment plans

based on genetic data. In Turkey, institutions such as Acıbadem and Koç University Hospitals are among the organizations integrating these technologies.

3.3. Agriculture: Precision Agriculture and Autonomous Systems

Industry 5.0 applications are also impacting the agricultural sector. Through precision agriculture techniques, processes such as soil fertility, irrigation, and fertilization are optimized using satellite data, sensors, and AI (Wolfert et al., 2017). Furthermore, autonomous tractors, harvest robots that collaborate with human operators, and agricultural drones are supporting farmers by enhancing labor productivity.

In Turkey, regions such as Şanlıurfa and Konya have accelerated the adoption of digital agricultural applications through projects supported by the Ministry of Agriculture and Forestry. These efforts contribute to reduced resource consumption and the fight against climate change.

3.4. Logistics and Supply Chain: Autonomous Logistics Systems

Industry 5.0 also aims to make supply chains more resilient and autonomous. Autonomous vehicles, drones, AI-based routing algorithms, and smart storage systems work in coordination with humans to enhance efficiency in logistics processes (Suryawanshi & Dutta, 2022). For instance, Amazon and Alibaba utilize autonomous robots working alongside humans within warehouses, and similar systems are becoming more widespread in Turkey, with pilot applications in companies like Trendyol. Furthermore, the supply chain crises triggered by the pandemic have further highlighted the need for resilient and intelligent systems. Table 2 discusses the sector-based applications of Industry 5.0.

Table 2: *Sector based applications of Industry 5.0*

Sector	Technologies Used	Expanded Key Applications
Manufacturing	Human-robot collaboration, AI, IoT, digital twins, 3D printing	- **Personalized production**: Mass customization of products to meet individual customer preferences. - **Collaborative robots (cobots)**: Safe, interactive robots working side-by-side with humans on complex tasks. - **Smart factories**: Integration of real-time data and digital twins to optimize production flows and predictive maintenance.
Healthcare	AI, wearable tech, robotics, digital twins, 5G	- **AI-assisted diagnostics**: Use of AI algorithms to detect diseases (e.g., cancer, neurological disorders) faster and more accurately. - **Robotic surgeries**: Precision surgeries

		supported by robotic systems. - **Personalized medicine**: Tailored treatment plans using genomics and patient data. - **Remote patient monitoring**: Continuous health tracking using IoT devices and wearables.
Agriculture	AI, drones, IoT, precision farming, robotics	- **Smart irrigation systems**: Automated water delivery based on real-time soil and weather data. - **Drone surveillance**: Monitoring crop health, detecting pests and diseases. - **Autonomous machinery**: Tractors and harvesters guided by AI and GPS. - **Soil and crop analytics**: Using AI to guide fertilization and planting decisions.
Logistics	Autonomous vehicles, AI, robotics, IoT	- **Warehouse automation**: Use of AI-powered robots and conveyors for efficient storage and retrieval. - **Smart route optimization**: Real-time traffic and weather data for dynamic delivery planning. - **Human-robot collaboration**: Workers and robots sharing tasks in fulfillment centers. - **Automated loading/unloading**: Mechanized systems for handling goods.
Supply Chain	Blockchain, AI, digital twins, big data analytics	- **Real-time tracking**: Live visibility of shipments and inventory using IoT and GPS. - **Predictive analytics**: Forecasting demand, delays, and risks using AI. - **Blockchain-based traceability**: Secure, transparent record of product origin and movement. - **Digital twins of supply networks**: Simulation and optimization of supply chain operations.

4. Industry 5.0 and Sustainability

Industry 5.0 represents a paradigm shift beyond the automation-centric focus of Industry 4.0, focusing the coordinated collaboration between humans and intelligent machines. It prioritizes human-centricity, resilience, and sustainability, aligning technological innovation with social and environmental goals. One of the core principles of Industry 5.0 is the integration of advanced technologies, (e.g., AI, IoT, and robotics) in a manner that

help improve human capabilities rather than replacing them (Nahavandi, 2019). This human-machine collaboration supports more flexible, customized, and ethical production processes that consider not only economic outcomes but also the well-being of workers and ecological impacts. By fostering personalized manufacturing and resource-efficient processes, Industry 5.0 sets a foundation for sustainable innovation ecosystems.

One of the primary objectives of Industry 5.0 is to restructure production processes not only in terms of efficiency but also within the framework of environmental and social responsibility. In this context, sustainability is an indispensable element of Industry 5.0, which prioritizes human-centered approaches and long-term welfare. The sustainable Industry 5.0 approach encompasses multi-dimensional applications such as reducing carbon emissions, improving energy efficiency, waste management, circular economy, and the integration of green technologies (Sharma, R., & Gupta, 2024).

The sustainability implications of Industry 5.0 are prominent, especially in addressing climate change, resource scarcity, and circular economy principles. Industry 5.0 can help companes to optimize supply chains, reduce energy consumption, and minimize waste generation, contributing directly to the United Nations Sustainable Development Goals (SDGs), through real-time data analytics and cognitive computing (Maddikunta et al., 2022). Furthermore, restoring the human element in industrial settings fosters inclusive innovation and promotes ethical governance, highlighting that sustainability extends beyond technological solutions to encompass broader societal responsibilities. As organizations increasingly adopt Industry 5.0 frameworks, the potential for achieving long-term environmental and social sustainability is enhanced, marking a critical evolution in the role of industry within the broader global sustainability agenda.

4.1. Carbon Footprint and Energy Efficiency

Industry 5.0 aims to transform energy-intensive production processes to generate more value with less energy. This is particularly achieved through the use of smart sensors, data analytics, and AI-supported energy management systems, which optimize energy consumption (Sarkar et al., 2024).

Furthermore, the reduction of fossil fuel consumption in production is supported by the wider use of renewable energy sources (such as solar, wind, and biomass). In alignment with the European Green Deal, Industry 5.0's goal of "carbon-neutral production" aims to reduce environmental pressure while enhancing the competitiveness of industrial organizations.

4.2. Circular Economy and Waste Management

The concept of sustainability necessitates the adoption of circular production models (reuse, recycle, remanufacture) over linear production models (take-make-dispose). Industry 5.0 offers technological and strategic infrastructure to accelerate this transition.

For instance:

- Through industrial symbiosis, the waste from one factory can serve as raw material for another factory.
- AI-supported waste monitoring systems facilitate the separation of recyclable materials.
- 3D printing reduces material waste, enabling production with minimal resources (Tavares et al., 2023).

In Turkey, circular production models are supported within the framework of zero-waste policies and green organized industrial zones (OSBs); some OSBs are beginning to develop integrated solutions using Industry 5.0 technologies.

4.3. Green Technologies and Ethical Production

Industry 5.0 is shaped not only by environmental considerations but also by ethical and social sustainability principles. Issues such as the prevention of child labor, protection of workers' rights, and occupational health and safety are prioritized in the production models of this era (Narkhede et al., 2025). Additionally, technologies like blockchain enhance supply chain transparency, making sustainable resource use traceable.

Green technologies are viewed not only as tools for environmental protection but also as components of innovation and competitiveness. In this regard, Industry 5.0 plays a crucial role as an interface for achieving sustainable development goals (SDGs). Table 3 presents the impact of Industry 5.0 on environmental, social and economic dimensions of sustainability.

Table 3: *Impact of Industry 5.0 on Sustainability*

Sustainability Dimensions/Subdimensions	**Impact of Industry 5.0 on Sustainability**
Environmental	
Energy Efficiency	Advanced human-machine collaboration optimizes production, reducing energy waste.
Waste Reduction	Mass customization and precision manufacturing lead to less material waste.
Circular Economy	Technologies enable easier recycling, reusability, and remanufacturing.
Carbon Footprint	Smart systems and localized production lower emissions and transportation needs.
Social	
Human-Centric Approach	Prioritizes worker well-being, safety, and meaningful roles alongside machines.
Job Enrichment	Automation handles repetitive tasks, freeing humans for creative, strategic work.
Inclusivity	Customizable tech can accommodate diverse needs (e.g., accessibility in workplaces).
Education & Upskilling	Focus on lifelong learning and human-machine

	synergy encourages skill development and knowledge sharing.
Economic	
Productivity	Collaborative robotics and AI improve efficiency without sacrificing personalization.
Innovation Acceleration	Faster product development cycles and responsive manufacturing boost competitiveness.
Resilience	Smart systems adapt to supply chain disruptions, enhancing economic stability.
Localized Production	Decentralized smart factories support local economies and reduce global overdependence.

5. Challenges and Opportunities of Industry 5.0

While Industry 5.0 presents numerous opportunities and innovations, it also faces several challenges. These challenges are related to technological, social, and economic changes, ethical issues, and infrastructure requirements. However, these challenges can be seen as barriers that must be overcome for Industry 5.0 to realize its full potential. Below, these challenges and opportunities are discussed in greater detail.

5.1. Challenges

- **Data Security and Privacy**: Industry 5.0 improves decision-making processes by collecting and processing large amounts of data. However, the security and privacy of this data is a significant concern. In particular, data analyses conducted via sensors, IoT devices, and artificial intelligence could lead to the misuse of personal data and cyberattacks (Ahmed et al., 2024). To overcome this issue, robust cybersecurity measures and data privacy policies are necessary.
- **Infrastructure Compatibility**: Unlike previous industrial revolutions, Industry 5.0 requires the integration of digitization and robotic systems. Existing infrastructures are often unsuitable for the integration of new technologies. This situation may result in high costs and technological incompatibility, especially in developing countries. This problem can be addressed through the adoption of new technologies, along with investments in training and infrastructure (Brynjolfsson, 2014).
- **Ethical and Social Issues**: The increasing collaboration between humans and robots brings ethical issues to the forefront. The impact of robots and AI systems on the workforce may raise concerns related to unemployment and social inequality. Furthermore, as Industry 5.0 embraces human-centered approaches, relying heavily on technology for decision-making may bring ethical and trust-related concerns (Panagou et al., 2024). Therefore, to ensure the success of a

human-centered and ethical Industry 5.0, appropriate ethical regulations and a sense of social responsibility are required.

5.2. Opportunities

- **Increased Productivity and Innovative Business Models**: Industry 5.0 enables the creation of more efficient and innovative business models by enhancing human-machine collaboration. In particular, personalized manufacturing and flexible work processes allow companies to increase both production speed and quality. This provides significant opportunities for firms aiming to gain a competitive advantage. Additionally, smart factories enable production processes to become faster, more cost-effective, and more environmentally friendly, thus supporting economic growth (Rüßmann et al., 2015).
- **New Industrial Models and Sectors**: Industry 5.0 enables the emergence of new industrial models and sectors, distinct from traditional manufacturing processes. Digitized service sectors, smart cities, green energy solutions, and digital health technologies present opportunities that contribute to economic growth. Furthermore, sustainability-focused solutions assist in the widespread adoption of environmentally friendly business models (Kolade and Owoseni, 2022).
- **Increased Workforce Productivity and Creativity**: One of the greatest opportunities offered by Industry 5.0 is the enhancement of workforce productivity and creativity. By taking over routine tasks, robots allow humans to focus on more creative, strategic, and innovative areas. This facilitates the emergence of more efficient and flexible production processes through human-machine collaboration, particularly in the manufacturing sector. Additionally, Industry 5.0 will give rise to new job roles. The demand for new workers such as data analysts, AI developers, and robotics technicians will increase (Lu et al., 2022).
- **Social Welfare and Human Rights**: Industry 5.0 supports a production model that enhances social welfare and respects human rights. Ethical production processes ensure that workers operate in safer and healthier environments. Moreover, the sustainability approach of Industry 5.0 could reduce environmental impact and contribute to the development of a more equitable societal structure (Canbay & Demircioğlu, 2021).

Industry 5.0 represents a paradigm shift in manufacturing, emphasizing the integration of human-centric values, sustainability, and technological innovation within production systems. However, challenges such as technological adaptation, ethical values, and infrastructure issues present barriers to this transformation. Nevertheless, Industry 5.0 offers opportunities for increased productivity, new business models, and social welfare, playing a crucial role in the future of the production world.

6. Conclusion and the Future of Industry 5.0

Industry 5.0 represents a significant evolution that shapes the future of industry. Built upon the foundations of Industry 4.0, this new industrial revolution is characterized by human-centered production, collaborative robots, artificial intelligence, and sustainable technologies. In the future, it is expected that the synergy between digitalization, AI systems, and robotic technologies will lead to the development of more sustainable and human-centric production models. This transformation aims to create a substantial impact not only technologically but also socially and environmentally.

Industry 5.0, through human-machine collaboration, offers the potential for faster production processes, higher quality, and customer-oriented solutions. In this era, where humans work more harmoniously with machines and environmentally friendly production processes take precedence, principles such as sustainability, resilience, and customization are at the forefront. One of the significant contributions of Industry 5.0 is making industrial sectors more efficient, flexible, and personalized. The integration of Industry 5.0 technologies into sectors like healthcare, agriculture, and logistics is offering innovative solutions and contributing to the sustainability of these industries.

However, Industry 5.0 also brings with it several challenges. Issues such as data security, ethical concerns, technological compatibility, and workforce transformation are fundamental barriers that need to be addressed for the successful implementation of this transformation. Overcoming these challenges will require not only technological solutions but also appropriate legal regulations, ethical approaches, and societal awareness. Additionally, robust infrastructure investments and environmentally friendly innovations are crucial for sustainable production processes.

The future of Industry 5.0 will necessitate significant changes in the workforce and education systems. Human-machine interaction will emphasize not only technical skills but also creative thinking, problem-solving, and ethical values. Therefore, to enable the next generation of the workforce to adapt to Industry 5.0, educational systems and workforce development programs will need to be restructured. This transformation will expand the skill sets of the workforce, creating higher-value jobs, and will aim to enhance societal welfare by adopting a human-centered production approach.

In conclusion, Industry 5.0 represents an industrial transformation focused on social responsibility and sustainability. The integration of technological innovations in ways that enhance human well-being presents significant opportunities not only for the industrial sector but also for society as a whole. For this transformation to succeed, a broad collaboration and a conscious approach at both industrial and societal levels are necessary.

Ethical Approval: *Ethics committee approval is not required in this study.*
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