The Industry of the Future: From Industry 4.0 to Industry 5.0 – Integration of Humans and Technology: New Technologies

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From Automation to Human-Centric Innovation: Embracing Industry 5.0 in Chemical Manufacturing

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Abstract: *The transition from Industry 4.0 to Industry 5.0 (I5.0) signals a transformative shift in industrial development, moving beyond automation and digitalization to prioritize sustainability, resilience, and human-centric innovation. This paper explores the emergence and application of I5.0 principles in the chemical manufacturing sector, a domain that has traditionally lagged in adopting digital transformation. By integrating technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), machine learning (ML), digital twins, and big data analytics, I5.0 offers a strategic framework for addressing pressing global challenges including climate change, supply chain disruptions, and ethical considerations.The paper presents a strategic model that emphasizes human - machine collaboration, aiming to optimize production while safeguarding ethical values, data integrity, and safety. Particular focus is placed on the responsible use of generative AI in chemical engineering, exploring both its transformative potential and the challenges it poses. Key technological advancements, such as predictive maintenance, real-time monitoring, robotics, and augmented reality are analyzed for their role in enhancing productivity, safety, and operational flexibility.Additionally, the digitalization of research and development is discussed as a driver for innovation, accelerating discovery through smart, self-optimizing platforms and continuous-flow chemistry. Advanced materials, additive manufacturing, and circular economy principles further support the sector's transition toward sustainable and adaptive systems.By embracing Industry 5.0, the chemical manufacturing industry can shift toward more inclusive, efficient, and ethically responsible practices. This evolution not only boosts industrial performance but also aligns production with broader societal and environmental goals. The paper concludes by positioning I5.0 as a necessary step for ensuring long-term industrial competitiveness and resilience in an increasingly complex global landscape.*

Keywords: *Industry 5.0, Chemical manufacturing, Artificial intelligence, Sustainability, Human-machine interaction, Augmented reality (AR), Continuous-flow chemistry.*

1. Introduction

The most literature on Industry 5.0 has been published since 2016, with 2020 marking a turning point in research focus, driven by the societal and environmental concerns amplified by the COVID-19 pandemic. India, China,

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and the United States are the leading contributors to Industry 5.0 research, with these countries needing a shift toward more sustainable economic models. Concepts like sustainable development, human-centricity, smart manufacturing, and 6G are well-established, while emerging topics include eco-innovation and communication. Industry 5.0 research highlights links to Industry 4.0 technologies like AI and blockchain but underrepresents labor-related concerns such as wages and job satisfaction [1].

The rise of smart factories has been fueled by advancements in the Internet and data storage technologies. In the early 2000s, industries adopted advanced sensors and automation, enabling the collection of large, precise datasets. Cloud computing and big data further enhanced the ability to process and analyze this information. Initially, smart factories focused on process-related data, but Industry 5.0 (I 5.0) now emphasizes human-machine interaction (HMI). This shift aims to improve collaboration between humans and technology in manufacturing. I5.0 integrates sustainability, resilience, and human-centricity into industrial value creation, gaining attention from policymakers and academia, though it is not widely adopted in the industry (Figure 1).

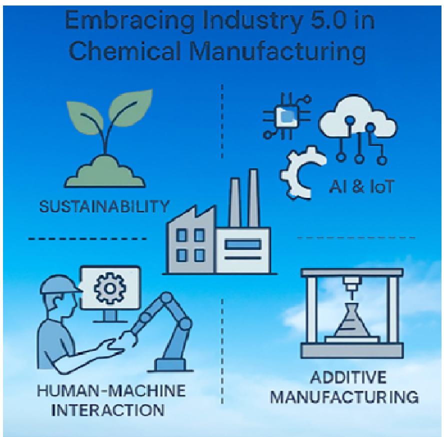

Figure 1. Schematic representation of the Industry 5.0 in chemical manufacturing

Many companies, especially SMEs, still focus on Industry 4.0 technologies but may find I5.0 more relevant in the coming years due to global challenges like climate change and geopolitical shifts [2]. Industry 4.0, introduced in 2011, integrates physical and digital systems to enhance automation and intelligence. Optimizing HMI is essential, as machines assist workers in decision-making while improving their well-being.

A key pillar of Industry 5.0 is human-centricity, aligning with the European Commission's priorities for an economy that benefits people. This vision also supports Europe's digital transformation and environmental goals outlined in the EU Green Deal [3-4]. Industry 5.0 combines human creativity with advanced automation to improve efficiency, productivity, and sustainability. It shifts manufacturing towards a more inclusive approach that integrates human intelligence and sustainable practices. This paradigm emphasizes balancing technological advancements with environmental responsibility and resource efficiency. Further research is needed to fully understand how AI, IoT, and robotics can contribute to sustainable industrial development [5].
Key features of I5.0 are shown in Figure 2.

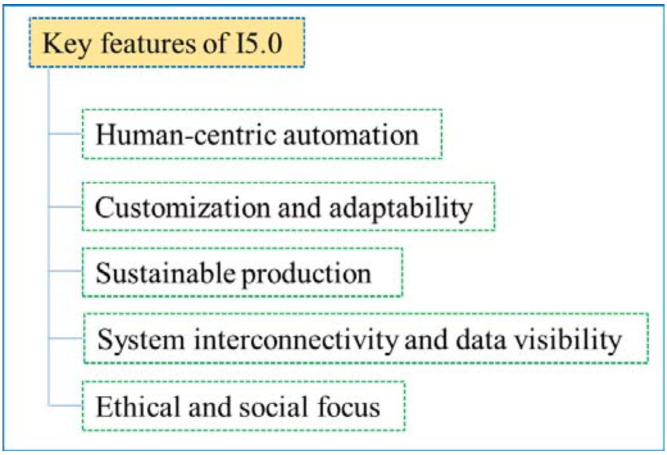

Figure 2. Key features of I5.0

Key features of I5.0 include[6]:
1. Human-centric automation focuses on enhancing human capabilities through collaboration with advanced technologies like artificial intelligence (AI) and robotics, rather than replacing human labor. The European Commission's 2021 Industry 5.0 (I5.0) framework aims to correct Industry 4.0's neglect of the human element by emphasizing human-centric innovation in smart factories [7]. However, the authors highlight ongoing gaps between the framework's vision and its practical implementation, particularly in how change processes are executed. They also point out a lack of depth in addressing work organization (WO), which is treated without sufficient differentiation or nuance.
2. Customization and adaptability highlight the move toward highly flexible manufacturing systems that can efficiently produce personalized products in smaller quantities, enabling quick responses to shifting market needs.

3. Sustainable production aims to minimize environmental impact by incorporating green practices, reducing waste, and maximizing resource efficiency throughout the production cycle.
4. System interconnectivity and data visibility leverage the Internet of Things (IoT) and AI to establish integrated networks that offer real-time analytics, boosting operational insight and informed decision-making.
5. Ethical and social focus ensures that technological advancements uphold values such as employee safety, fair working conditions, and broader social well-being.

Human-centricity
Food 4.0 focused on automation to optimize production but led to job displacement. In contrast, Food 5.0 prioritizes human empowerment by fostering collaboration between humans and technology. Instead of replacing workers, it enhances their capabilities through innovations like cobots in baking and AR for maintenance. The goal is a symbiotic relationship between humans and machines [8].

Sustainability
Food 5.0 aims to create a sustainable, efficient food ecosystem by adopting circular economy principles and minimizing waste. Unavoidable waste is repurposed for food, animal feed, or biofuel. Innovations like whey protein extraction and insect protein production enhance sustainability. Governments support these efforts through regulations and incentives.
Industry 5.0 further promotes sustainability by integrating IoT and advanced bioenergy systems, such as algae-based biofuels, reducing fossil fuel reliance and emissions. Optimized bio-refineries cut energy use by up to 40%, while smart resource management reduces waste by 20-30%. These advancements drive energy efficiency and sustainability in industrial processes[8].

Resilience - the ability to recover from adversity - is vital for managing disruptions in global food supply chains, which face threats from conflicts, climate change, and pandemics. Recent crises highlight their fragility, leading to food and labor shortages. However, technologies like IoT and big data enable real-time responses, strengthening supply chain resilience. Investing in these advancements ensures food security and safety amid an unpredictable world[8].
A recent study found that AI-driven irrigation systems can save up to 27.6% of water and 57% of energy by optimizing schedules, preventing overwatering, and maintaining ideal soil moisture levels[9].
The Adaptive Smart Factory (ASF) concept transforms traditional food production into automated, flexible, and digitalized systems. A process-product

innovation model helps SMEs adopt Industry 5.0 by integrating agile strategies and Society 5.0 principles.

Applying process reengineering to pasta production has led to a 20% increase in output, 40% less raw material waste, 80% lower machine maintenance costs, 90% reduced production failure risks, and a 60% improvement in quality[10].

Employees in Industry 5.0 fall into two categories: ***professionals*** using advanced HMI to enhance expertise and ***non-professionals*** requiring user-friendly interfaces. Effective HMI design should reduce workload, boost well-being, and encourage creativity. Sustainability and resilience are key pillars of Industry 5.0, driven by global challenges like pandemics and climate change. Emerging technologies such as Artificial Intelligence (AI), machine learning (ML), Virtual Reality (VR), and digital twins strengthen predictive maintenance and operational efficiency. The future of manufacturing depends on seamlessly integrating these technologies with human workers[11].

Augmented reality (AR) is a technology that overlays digital content - such as audio, visuals, and text - onto the real-world environment to enrich user experiences by enabling interactive engagement with physical surroundings. As tools and hardware supporting AR have advanced and become more widely available, its importance as a key driver of Industry 4.0 and industrial digitalization has grown significantly, making it increasingly accessible and easier to use.According to Moreira et al. (2024) [12] the practical implementation of AR within the chemical industries remains surprisingly limited. Despite the broader appeal of virtual reality (VR) and mixed reality (MR), augmented reality (AR) remains **essential**in high-risk industrial settings due to its real-time data integration and ability to support situational awareness without isolating users from their environment. The unique demands of the chemical industry make it **essential**to evaluate AR not merely as an optional enhancement, but as a core tool that can improve safety, efficiency, and operational continuity. As industries face increasingly complex challenges, adopting AR as an **essential** component of their digital transformation strategy can help bridge the gap between its demonstrated potential and current limited practical application [12].

A 2020 report found that 80% of surveyed companies have started their digitalization journey, with large enterprises leading the way, including companies like Nokia, Siemens, and Intel. Digitalization is increasingly recognized as a competitive advantage in the industrial sector, and companies that fail to adopt it risk falling behind. Governments, including those in Germany, France, and the UK, have supported digitalization with plans and funding to help industries stay competitive. However, the chemical process industry has been slow to adopt digital technologies, with a 2023 McKinsey report revealing underutilization, and only 35% of chemical companies in the digitalization rollout phase[13].

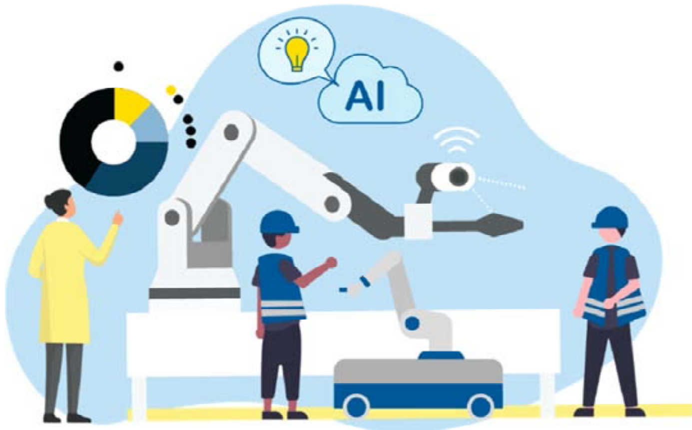

Figure 3. Human-machine teams make the most of both the expertise of each team member and the advanced abilities of smart machines[14].

The concept of Industry 5.0 envisions future factories that are sustainable, resilient, and human-centered, relying on advanced capabilities from both next-generation manufacturing systems and human operators.

2. Chemical Manufacturing

Chemical manufacturing is constantly advancing as new technologies enhance efficiency, productivity, and sustainability. Breakthrough materials and innovative processes are transforming production methods, creating fresh opportunities while tackling key challenges in the industry.A major breakthrough in chemical manufacturing is the streamlining of production processes and the reduction of resource usage [15].
Conventional batch methods are gradually giving way to continuous production, in which reactions occur within a steady flow system. This method enables greater precision, shorter reaction durations, and improved product output. In addition, continuous production minimizes waste and lowers energy use, making manufacturing more sustainable and economical[16].
Sustainable manufacturing has evolved from minimizing environmental impacts to promoting economic, environmental, and social sustainability. Industry 4.0 has supported sustainability at the firm level through innovations like the Industrial Internet of Things (IIoT) and additive manufacturing, which reduce waste and energy consumption. However, concerns remain about the broader socio-environmental impacts of Industry 4.0, particularly regarding job displacement and energy conservation. In response, the Industry 5.0 agenda aims

to address these issues by promoting human-centric, sustainable manufacturing practices. Research into Industry 5.0's potential to foster sustainable manufacturing is still in its early stages, with a focus on understanding its functions and how they can be leveraged effectively[17].

2.1 Generative Artificial Intelligence in Chemical Engineering

Generative artificial intelligence (AI) is capable of creating new content after being trained on data, including text, images, and other media types, with applications in various fields. In chemical engineering, there has been a shift towards focusing on efficiency and sustainability, driven by the need to reduce energy use and environmental impact [18]. Generative AI has started to streamline processes in the sector, such as improving warning systems, answering technical questions, and generating computer code. However, to maximize its benefits, a proactive approach is needed to integrate ethical considerations and safety standards, ensuring that generative AI can be safely and effectively used in chemical engineering.

Engineering ethics are essential for professionals, recognizing their impact on society both positively and negatively. The Royal Academy of Engineering emphasizes principles like honesty, respect for life, public good, and integrity. In chemical engineering, neglecting these ethics can lead to severe, discipline-specific disasters. Chemical engineers are particularly equipped to address safety and environmental concerns, key aspects of their field. As generative AI becomes more integrated into the industry, chemical engineers are well-positioned to manage both the technical and ethical challenges it presents[18].

Societal issues in chemical engineering, especially concerning the potential dangers of chemicals, must be considered, as generative AI models like LLMs could be misused to create harmful substances. While some safeguards exist in AI models, they are reactive rather than proactive, highlighting the need for inherently safer AI development. Chemical engineers, responsible for safety from design to implementation, must ensure AI tools meet strict safety standards. Issues such as automating engineering diagrams raise concerns about the potential for disastrous outcomes without thorough assessment. Responsible AI use in chemical engineering should focus on its impact on individuals and society, with safe data collection and transparent AI model development[18].

A major challenge in using generative AI for flow sheet automation is the lack of publicly available or machine-readable databases, limiting the quality of AI models. Current attempts at automating flow sheets often fail to integrate physical knowledge, resulting in functionally meaningless outputs. Without a responsible approach, AI-generated flow sheets may contain errors or redundancies, leading to safety hazards if poorly understood designs are rushed into development. To address this, new standards should be established to ensure all flow charts are machine-readable. Despite these challenges, generative AI has shown promise in areas like electrode design, demonstrating potential in materials and structures development[18].

The integration of physics-based and data-driven models offers opportunities for advancing electrochemical technologies like fuel cells and batteries, which are crucial for green systems and decarbonization. As generative AI becomes more prevalent in chemical engineering, its responsible use will require a multi-faceted approach, combining technology, people, and regulations. Adhering to responsible AI principles—such as ensuring AI is lawful, ethical, and robust - will foster trust and acceptance, similar to maintaining public trust in chemical processes. For AI to be trustworthy, it must be explainable and verifiable, integrating expert knowledge with machine learning to improve decision-making speed and accuracy. Ultimately, the development of explainable AI (XAI) will be crucial in ensuring transparency, accountability, and trust in the models used in chemical engineering[18].

A people-centered approach to responsible Generative AI in chemical engineering focuses on designing systems that best serve the users, considering their needs from the start to ensure synergy between human expertise and AI tools. By applying lessons from the industry's safety culture, AI systems must be designed to work with chemical engineers in a safe and effective manner, preventing unintended consequences. Tools like AI-assisted HAZOPs show potential to improve work speed and quality, but they must be thoroughly reviewed to avoid disasters and maintain trust in AI's role in the sector. Strong leadership and clear communication are crucial to integrating responsible AI use, as is fostering a culture that upholds accountability, safety, and transparency. As AI becomes more integrated into chemical engineering, maintaining high standards of honesty, accuracy, and rigor will be essential to avoid shortcuts and mistakes, with leadership setting the tone for responsible AI practices[18].

2.2 Digital Transformation in Research and Development in Chemical Manufacturing

Industry 4.0 focuses on automation and advanced technologies, while Industry 5.0 strengthens collaboration between humans and machines. In the chemical sector, the use of digital tools such as artificial intelligence, robotics, and predictive maintenance is improving efficiency and lowering costs. Research and development is one of the most important areas for digital transformation (Figure 4). Digital twin technology, which creates virtual models of real processes, enables safe and efficient testing. This reduces risks, saves time and money, and increases the profitability of research and development projects.

2.2.1 Document Management Systems

Numerous chemical companies rely on digital tools like document management systems, which provide structured documentation of process and data flows. These systems make it possible to digitally organize and handle the vast amounts of documents and data produced during the research stage.

2.2.2 Networking

Creating a new product usually requires collaboration across multiple departments and employees, often spread across different locations in large organizations. Through digital transformation, virtual networks allow seamless data sharing and communication among colleagues, significantly improving the efficiency of research and development projects.

2.2.3 Big Data

Across all sectors, the volume of data to be processed is rapidly growing, often referred to as big data. To interpret this information, chemical companies require effective digital solutions. Such tools create a strong basis for the focused development of innovative products.

2.2.4 Artificial Intelligence

Artificial intelligence was already widely used across different industries before the rise of ChatGPT, which has since made the technology more accessible to everyone. In chemical companies, AI holds significant potential for research and development by enabling automated analysis and interpretation of experiments. Through machine learning and AI algorithms, production processes can be optimized, outcomes predicted, and R&D accelerated. By examining large data sets, AI models detect patterns and refine reaction conditions, leading to better product quality, shorter cycle times, and lower waste generation.

Kanarik and Osowiecki[19]investigate the use of Bayesian optimization algorithms to evaluate how artificial intelligence can reduce the cost of developing complex semiconductor chip processes. They designed a controlled virtual process simulation to systematically compare the performance of human engineers and computer algorithms in semiconductor fabrication. The results show that human engineers perform best during the early stages of development, while algorithms are more cost-efficient as the process approaches precise target specifications. The study also demonstrates that combining expert human designers with AI in a strategy that prioritizes humans first and computers last can cut the cost-to-target by fifty percent compared to using only human designers.

2.2.5 Machine Learning

Artificial intelligence also encompasses machine learning tools, which not only manage existing processes but can also learn new ones. Leveraging these capabilities, they support research and development by generating ideas for new formulations. Machine learning algorithms aid in designing formulations, predicting material properties, and optimizing reaction pathways. These technologies promote faster innovation, more efficient decision-making, and improved product development.

2.2.6 Internet of Things (IoT)

The Internet of Things (IoT) bridges the physical and digital worlds. A common example is a smart refrigerator that can detect when supplies run low and automatically reorder items. In the chemical industry, IoT facilitates the digital monitoring of changes in physical systems during research and development. Sensors, connected devices, and data analytics platforms provide detailed information on production conditions, energy usage, and equipment performance. Using this data, companies can optimize processes, anticipate maintenance needs, and identify opportunities to improve efficiency. Additionally, digitalization strengthens supply chain management by allowing real-time monitoring of raw materials, inventory, and product shipments.

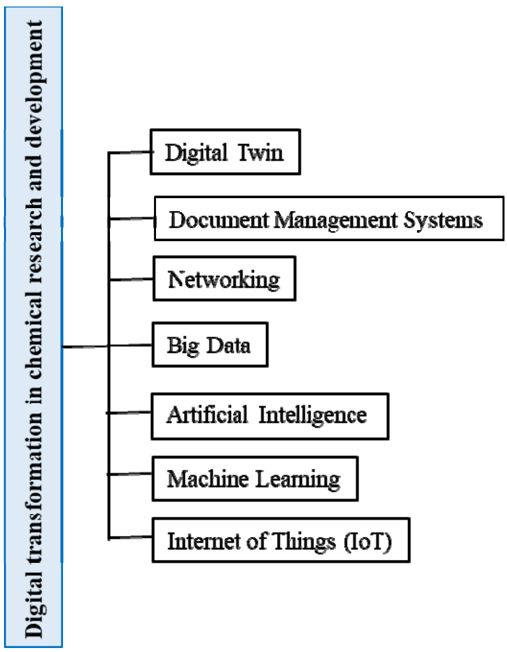

Figure 4. Digital transformation in chemical research and development

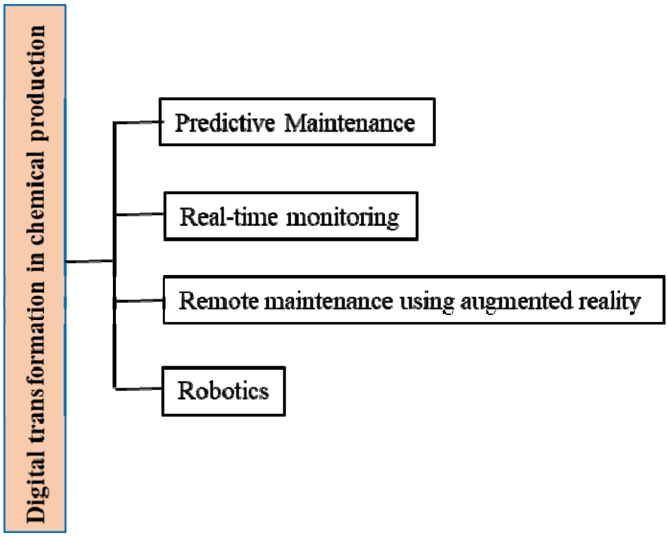

Figure 5. Digital transformation in chemical production

Digitalization holds significant potential in research and development, but the chemical industry is increasingly using digital tools for the next step - production (Figure 5). This involves automation, which streamlines operations and boosts efficiency.

2.2.7 Predictive Maintenance

Machine failures are among the most significant threats to production. Predictive maintenance tools can identify and resolve potential issues before they lead to breakdowns. By detecting early deviations and alerting the company in advance, these tools allow timely interventions and help prevent interruptions in production.

2.2.8 Real-Time Monitoring

Accurate combination of raw materials is essential for producing safe chemical products. Digitalization plays a key role by enabling real-time monitoring of raw materials, mixtures, and finished products. This allows manufacturers to quickly detect and respond to any deviations during production.

2.2.9 Remote Maintenance with Augmented Reality

Whether a problem is identified in advance or a real breakdown occurs in the chemical industry, machine reconditioning and operation are crucial. With augmented reality, maintenance becomes easier, problem-solving quicker, and all tasks can be performed regardless of location. In many cases, technical experts don't even need to be on-site. In short, augmented reality can simplify and optimize maintenance and repairs.

2.2.10 Robotics

Every manufacturing step brings challenges, some of which are repetitive. Robots are valuable in performing repetitive tasks due to their specialized capabilities. Automation and robotics are reshaping chemical production by enhancing precision, accuracy, and safety. They are employed in activities such as sample handling, ingredient measurement, and packaging. By automating these processes, companies reduce human errors, boost productivity, and protect workers from exposure to hazardous materials. Additionally, robotic systems can operate in challenging environments and consistently carry out repetitive tasks with high efficiency.

2.3 Chemical Industry: Digital Security and Data Protection

Digitalization streamlines everyday operations for companies in the chemical industry, but it also raises concerns about cybersecurity and data protection. The risk of unauthorized access to sensitive information is a common worry, particularly with cloud-based solutions. These concerns can be mitigated by selecting secure and reliable systems. Equally crucial is the safe management of chemical substances, which digital tools can support effectively. Overall, chemical companies must carefully address and critically evaluate security issues throughout their digital transformation [20].

2.3.1 Digital Transformation is Accelerating

The collected and properly connected data from industrial plants and digital twins play a decisive role in leveraging the advantages and potential of Industry 5.0 in the chemical sector, with its specific challenges. The integration of IoT and artificial intelligence allows companies to respond more quickly and flexibly to changes in the market and evolving customer needs. At the same time, emphasis is placed on protecting investments and managing total cost of ownership through customized and sustainable solutions. This includes smarter plant startups, faster engineering, and efficient commissioning, as well as maintaining high productivity, operational uptime, safe and adaptable production, and sustainability and security throughout the plant’s lifecycle. Additionally, asset availability is maximized through the use of big data analytics and artificial intelligence [21]. Technological progress is transforming chemical manufacturing by improving efficiency, sustainability, and product quality. Enhanced process methods, automation, digital technologies, advanced materials, additive manufacturing, and AI-based techniques are changing the way the industry operates, helping producers meet increasing demand while minimizing environmental impact. By adopting these innovations, the chemical sector can create new opportunities, drive innovation, and support a more sustainable future.

2.3.2 Advanced Materials and Sustainable Solutions

Progress in chemical manufacturing includes the creation of advanced materials with improved performance and greater sustainability. Researchers are developing new formulations, ranging from bio-based materials to lightweight composites, that minimize environmental impact while maintaining functionality. These materials find applications in industries such as automotive, aerospace, and renewable energy. At the same time, sustainable production practices, including green chemistry and circular economy approaches, are becoming increasingly important, encouraging resource efficiency and reducing waste.

2.3.3 Additive Manufacturing (3D Printing)

Additive manufacturing, commonly referred to as 3D printing, is transforming the production of customized chemical products and components. This technology enables the fabrication of intricate structures, complex geometries, and functional prototypes while minimizing material waste. It also supports on-demand production, reducing the need for extensive inventory. In chemical manufacturing, 3D printing is applied to catalysts, drug delivery systems, and bespoke chemical reactors, allowing for more efficient and tailored solutions.

Traditionally, chemical synthesis has depended on labor-intensive batch processes, but the push for novel reactions and sustainable methods is changing this landscape. Smart, self-optimizing platforms and advanced analytical tools now enhance synthesis efficiency. Machine-assisted approaches improve resource management, enabling chemists to concentrate on discovery and experimental planning. The integration of continuous-flow chemistry with batch methods expands control and process capabilities. Emerging technologies such as AI, augmented reality, and automation are reshaping laboratory management and experiment monitoring. Nonetheless, chemical synthesis remains complex, requiring human expertise in combination with advanced tools. Ongoing innovations in flow chemistry, reaction monitoring, and automation continue to advance the capabilities of chemical manufacturing [22].

2.4 Digital Transformation in the Chemical Industry

Digitalization is transforming all sectors of the chemical industry ranging from petrochemicals to agrochemicals by enhancing productivity, optimizing supply chains, and expanding market reach. A notable example is the 2021 collaboration between Siemens and Dow, which led to the creation of a process automation test bed aimed at accelerating the adoption of digital twins in chemical manufacturing. Key growth drivers include the demand for efficient,

continuous production, increased adoption of digital technologies, and the need for better batch scheduling. Government investments in R&D and the rise of technologies like IoT, AI, VR, and 3D printing are further boosting innovation and digital transformation in the sector. Despite these advances, barriers such as high implementation costs, limited technical knowledge, and regulatory constraints pose challenges. The market for digital solutions in the chemical industry was valued at USD 15.81 billion in 2023 and is projected to grow to USD 75.69 billion by 2031, with a strong CAGR of 21.7%. Key findings highlight IoT adoption, environmental concerns, and North America's market dominance, while cost-related hurdles remain a primary challenge to broader digital integration (Figure 6) [23].
Increasing awareness of sustainability is prompting the chemical industry to reassess its operations and pursue environmentally friendly alternatives that reduce ecological impact and promote resource conservation. By leveraging advanced data management, reliable AI models, and versatile algorithms, digital transformation is reshaping the chemical sector offering powerful opportunities to integrate sustainable and innovative practices into routine processes[24].

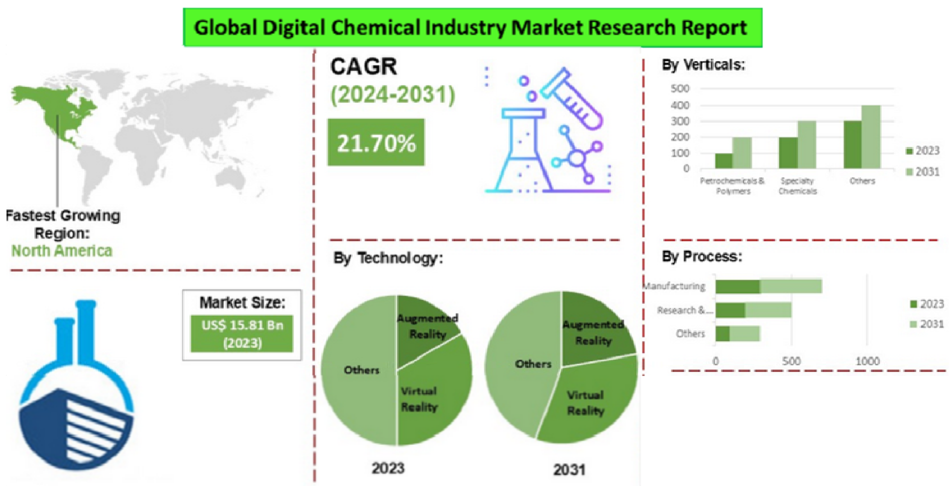

Figure 6. Global Digital Chemical Industry Market

Augmented reality (AR) enhances user interaction by superimposing digital content onto the physical environment, creating a more immersive and engaging experience.It has become a key enabler in Industry 4.0 due to advancements in hardware and software. Unlike virtual reality, AR integrates synthetic elements while maintaining the dominance of the natural environment. Its applications span multiple fields, including medicine, entertainment, and education. Industries such as manufacturing, construction, and energy are leveraging AR to enhance processes and efficiency. AR is reshaping workflows and driving innovation across various sectors. As technology advances, AR's impact on industrial transformation is expected to grow significantly.

Augmented reality (AR) plays a crucial role in high-risk industrial environments by providing real-time information overlays and maintaining situational awareness. While virtual reality (VR) and mixed reality (MR) are useful for immersive training in hazardous scenarios, AR integrates seamlessly into existing workflows. The choice between AR, VR, and MR should depend on specific operational and safety needs rather than assuming one is superior. In chemical industries, MR may be better suited for immersive training, while AR excels in real-time guidance. A hybrid approach could optimize safety and efficiency by leveraging each technology's strengths. This study reviews the current state of AR in industrial settings, highlighting its potential and implementation challenges. It aims to bridge the gap between AR's capabilities and its practical application in industry [12].

Technological innovation involves introducing new or enhanced ideas, processes, or technologies that drive improvements in efficiency, performance, and competitiveness, especially in manufacturing. While Industry 4.0 has leveraged these innovations to digitally transform production through automation and interconnected systems, Industry 5.0 builds on this foundation by prioritizing sustainability, aiming to create more resilient and eco-friendly industrial ecosystems. The evolving relationship between technology and sustainability highlights the importance of integrating both for long-term corporate success, marking a shift from their once-perceived incompatibility toward a new paradigm of sustainable innovation.

Vacchi eta l. 2024 [25] validated the Process Technological Sustainability Assessment (P-TSA) framework - aligned with the ISO 14040 life cycle approach through its application in a ceramic tile manufacturing company, revealing its effectiveness in measuring technological sustainability via key impact categories: input/output availability (IOA), operational performance (OP), and technical quality (TQ). By developing and weighting specific indicators, the framework generated a Process Technological Sustainability Index (P-TSI), which reflected changes in sustainability performance between 2017 and 2022. Key findings showed that production interruptions (e.g., maintenance, pandemics) negatively affected IOA, while increased production volumes and strong inventory management had a stabilizing effect; however, technological upgrades like digitalization sometimes reduced technical quality scores. The study also emphasized the importance of life cycle thinking, ethical sourcing, and cross-sector collaboration in embedding sustainable practices into industrial innovation, offering both theoretical insights and practical guidance for sustainable manufacturing.

2.5 The Role of Ethics in Industry 5.0

As human–machine collaboration increases in Industry 5.0, ethical concerns about technology's impact on humans are growing. Ethics plays a crucial role in balancing self-interest and societal good while fostering a symbiotic relationship between humans and the cyber-physical world. While research on ethical issues in technology is expanding, it often focuses on individual values or specific technologies, such as ICT and robotics, rather than a holistic approach. Despite some efforts to explore ethical implications in industrial settings, most research remains limited and disproportionately emphasizes technical aspects over ethical considerations [26].

Society 5.0 prioritizes human well-being by using technology ethically to enhance lives across various sectors, including healthcare, education, and sustainability. It views technology as a tool for empowerment, inclusivity, and addressing societal challenges rather than an end in itself. Industry 5.0 builds on this vision by integrating technology with sustainable and people-centric operational systems, though its impact on supply chains remains uncertain. While Industry 4.0 aimed for sustainability, gaps in addressing key issues led to the emergence of Industry 5.0. Additionally, the rise of ChatGPT signifies a shift from algorithmic to linguistic intelligence, emphasizing real-time human-machine interactions [27].

Vidhani and Mariappan[28]highlights the importance of effective communication in guiding ChatGPT-3.5 to provide accurate and reliable responses, especially in chemistry. It finds that clearly defining terms and context in prompts improves response accuracy, as seen in chemistry topics like the isoelectronic series, while excessive elaboration can cause confusion. Using direct, field-specific questions such as in electron affinity or ionization equations proved to enhance the reliability of the responses, while iterative prompt refinement through trial and error helped achieve better results. The study also emphasizes the critical role of human oversight and suggests integrating ChatGPT-3.5 into education to foster critical thinking, allowing students to analyze and verify AI-generated outputs.

3. Conclusion

The evolution from Industry 4.0 to Industry 5.0 marks a critical inflection point for the chemical manufacturing sector. While digitalization and automation have laid the groundwork for operational efficiency, the future demands a more holistic approach - one that integrates technological advancement with sustainability, resilience, and human-centric values. Industry 5.0 enables this transition by fostering intelligent, adaptable, and ethical manufacturing systems.The integration of AI, IoT, digital twins, machine learning, and augmented reality is already reshaping the chemical industry, enhancing predictive maintenance, real-time monitoring, and remote operations. These technologies not only boost productivity but also reduce risks, improve worker safety, and enable faster, more informed decision-making. Meanwhile, emerging practices such as additive manufacturing, continuous-flow chemistry, and the development of advanced materials contribute to greater flexibility, efficiency, and environmental responsibility.Equally important is the responsible and ethical use of these technologies-particularly generative AI-within chemical engineering processes. Addressing concerns related to digital security, data integrity, and human oversight is essential for building trust and ensuring sustainable innovation.This paper underscores that Industry 5.0 is not merely an upgrade of existing systems but a fundamental rethinking of industrial operations. It positions human creativity and well-being at the center of technological development, aligning production with broader societal needs. For the chemical manufacturing industry, adopting I5.0 principles is not only a pathway to enhanced performance and competitiveness but also a necessary step toward achieving long-term environmental and social goals.As global challenges continue to intensify, the ability to innovate ethically, operate flexibly, and design for resilience will determine the future success of industrial sectors. Industry 5.0 provides the framework to meet these demands, enabling a smarter, more inclusive, and sustainable industrial era. The future research in areas like human-machine collaboration, sustainable production, cybersecurity, ethical implications, and the development of new business models within the context of Industry 5.0 is recommended.

4. References

[1] Ben Youssef, A., & Mejri, I. (2023) Linking digital technologies to sustainability through Industry 5.0: A bibliometric analysis. *Sustainability, 15*(9), 7465. https://doi.org/10.3390/su15097465

[2] van Erp, T., Carvalho, N. G. P., Gerolamo, M. C., Gonçalves, R., Rytter, N. G. M., & Gladysz, B. (2024). Industry 5.0: A new strategy framework for sustainability management and beyond. *Journal of Cleaner Production, 461*, 142271. https://doi.org/10.1016/j.jclepro.2024.142271

[3] Bratovčić, A. (2024) Modern methods of transforming chemical processes for sustainable production. *Infokom Science Journal of Contemporary Economics*, *2*(1), 62–76.

[4] European Commission, Directorate-General for Research and Innovation, Renda, A., SchwaagSerger, S.,Tataj, D. et al., Industry 5.0, A transformative vision for Europe – Governing systemic transformationstowards a sustainable industry, Publications Office of the European Union,2021, https://data.europa.eu/doi/10.2777/17322

[5] Rame, R., Purwanto, P., & Sudarno, S. (2024). Industry 5.0 and sustainability: An overview of emerging trends and challenges for a green future. *Innovation and Green Development, 3(4)*, 100173. https://doi.org/10.1016/j.igd.2024.100173

[6] Pasman, H. J., & Behie, S. W. (2024). The evolution to Industry 5.0 / Safety 5.0, the developments in society, and implications for industry management. *Journal of Safety and Sustainability, 1*(4), 202–211. https://doi.org/10.1016/j.jsasus.2024.11.003

[7] European Commission. *Industry 5.0: A transformative vision for Europe: towards a sustainable, human-centric and resilient European industry*. 2021. https://research-and-innovation.ec.europa.eu/knowledge-publications-tools-and-data/publications/all-publications/industry-50-towards-sustainable-human-centric-and-resilient-european-industry_en

[8] Abdo Hassoun, S., Jagtap, S., Trollman, H., Garcia-Garcia, G., Duong, L. N. K., Saxena, P., Bouzembrak, Y., Treiblmaier, H., Para-López, C., Carmona-Torres, C., Dev, K., Mhlanga, D., &Aït-Kaddour, A. (2024). From Food Industry 4.0 to Food Industry 5.0: Identifying technological enablers and potential future applications in the food sector. *Comprehensive Reviews in Food Science and Food Security, 23*(6), e370040. https://doi.org/10.1111/1541-4337.70040

[9] Preite, L., & Vignali, G. (2024). Artificial intelligence to optimize water consumption in agriculture: A predictive algorithm-based irrigation management system. *Computers and Electronics in Agriculture, 223*, 109126. https://doi.org/10.1016/j.compag.2024.109126

[10] Massaro, A., & Galiano, A. (2020). Re-engineering process in a food factory: An overview of technologies and approaches for the design of pasta production processes. *Production & Manufacturing Research, 8*(1), 80–100. https://doi.org/10.1080/21693277.2020.1749180

[11] Yang, J., Liu, Y., & Morgan, P. L. (2024). Human–machine interaction towards Industry 5.0: Human-centric smart manufacturing. *Digital Engineering, 2*, 100013. https://doi.org/10.1016/j.dte.2024.100013

[12] Moreira, L.C.d.S.; Rebello, C.M.; Costa, E.A.; Sanchez, A.S.; Ribeiro, L.S.; Nogueira, I.B.R. Digital Transformation in the ChemicalIndustry: The Potential of Augmented Reality and Digital Twin. *Appl. Sci*. 2024, 14, 11607. https://doi.org/10.3390/app142411607

[13] Pietrasik, M., Wilbik, A., & Grefen, P. (2024). The enabling technologies for digitalization in the chemical process industry. *Digital Chemical Engineering, 12*, 100161. https://doi.org/10.1016/j.dche.2024.100161

[14] Kaasinen, E., Anttila, A.-H., Heikkilä, P., Laarni, J., Koskinen, H., & Väätänen, A. (2022). Smooth and resilient human–machine teamwork as an Industry 5.0 design challenge. *Sustainability, 14*(5), 2773. https://doi.org/10.3390/su14052773

[15] Bratovcic, A. Implementation of Artificial Intelligence, Smart Sensors, Robots and Digital Transformation in Food and Agricultural Production. *ARTIFICIAL INTELLIGENCE IN INDUSTRY 4.0: THE FUTURE THAT COMES TRUE*, 221.

[16] Advancements in Chemical Manufacturing: Exploring the Latest Technological Innovations, (2023) https://intimedia.id/read/advancements-in-chemical-manufacturing-exploring-the-latest-technological-innovations

[17] Ghobakhloo, M., Iranmanesh, M., Foroughi, B., Babaee Tirkolaee, E., Asadi, S., & Amran, A. (2023). Industry 5.0 implications for inclusive sustainable manufacturing: An evidence-knowledge-based strategic roadmap. *Journal of Cleaner Production, 417*, 138023. https://doi.org/10.1016/j.jclepro.2023.138023

[18] Daniel, T., & Xuan, J. (2024). Responsible use of generative AI in chemical engineering. *Digital Chemical Engineering*, 12, 100168. https://doi.org/10.1016/j.dche.2024.100168

[19] Kanarik, K. J., Osowiecki, W. T., Lu, Y., et al. (2023). Human–machine collaboration for improving semiconductor process development. *Nature, 616*, 707–711. https://doi.org/10.1038/s41586-023-05773-7

[20] Bernardt, S. (2023)Digitalization in the Chemical Industry https://www.yaveon.com/en/about-yaveon/blog/digitalization-chemical-industry/#pp-toc-0m5r6wc1hb7l-anchor-0

[21] Digital transformation, Siemens, accessed on 21.04.2025. https://xcelerator.siemens.com/global/en/all-offerings/products/d/digital-transformation.html

[22] Ley, S. V. (2018). The engineering of chemical synthesis: Humans and machines working in harmony. *AngewandteChemie International Edition, 57*(17), 5182–5183. https://doi.org/10.1002/anie.201802383

[23] Global Digital Chemical Industry Market(2024) (Report ID: 1190). https://www.insightaceanalytic.com/report/global-digital-chemical-industry-market-/1190

[24] Sexton, J. (2023, September 23). *Digital transformation in the chemical industry: Steps to a sustainable future*. CAS Insights. https://www.cas.org/resources/cas-insights/digital-transformation-chemical-industry-steps-sustainable-future#transitioning-to-sustainable-chemistry-meeting-ever-changing-regulatory-demands

[25] Vacchi, M., Siligardi, C., &Settembre-Blundo, D. (2024). Driving manufacturing companies toward Industry 5.0: A strategic framework for process technological sustainability assessment (P-TSA).*Sustainability, 16*(2), 695.https://doi.org/10.3390/su16020695

[26] Longo, F., Padovano, A., &Umbrello, S. (2020) Value-oriented and ethical technology engineering in Industry 5.0: A human-centric perspective for the

design of the factory of the future. *Applied Sciences, 10*(12), 4182. https://doi.org/10.3390/app10124182

[27] El Zein, B., Elrashidi, A., Dahlan, M., Al Jarwan, A., & Jabbour, G. (2024) Perspective Chapter: Nano and Society 5.0 – Advancing the Human-Centric Revolution. IntechOpen. doi: 10.5772/intechopen.1004221

[28] Vidhani, D. V., & Mariappan, M. (2024) Optimizing human–AI collaboration in chemistry: A case study on enhancing generative AI responses through prompt engineering. *Chemistry, 6*, 723–737. https://doi.org/10.3390/chemistry6040043