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SMART MANUFACTURING ON THE HORIZON: A Conceptual Shift from Industry 4.0 to Industry 5.0: Industrija

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Industry 4.0 and Green Chemistry Integration for Sustainable Smart Chemical Manufacturing

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Abstract: *The chemical industry is undergoing a rapid digital transformation driven by Industry 4.0 technologies and data-driven innovation. Evolving from Cyber-Physical Production Systems, Industry 4.0 integrates Internet of Things (IoT), artificial intelligence (AI), machine learning (ML), big data analytics, robotics, and cloud computing to enable smart manufacturing systems with real-time monitoring, automated control, predictive maintenance, and enhanced decision-making. These capabilities significantly improve process efficiency, safety, and operational flexibility. In parallel, Green Chemistry principles enhance sustainability by promoting pollution prevention, resource efficiency, and the use of safer and renewable feedstocks. The integration of smart manufacturing with Green Chemistry has created sustainable production systems where environmental and economic performance are jointly optimized. Digital twins and process simulation further support virtual optimization, reducing experimental costs and accelerating process development. Beyond manufacturing, AI-, ML-, and modeling-driven approaches are transforming chemical research, particularly in catalysis, through high-throughput screening, predictive modeling, and multiscale analysis. These methods, supported by digital platforms, are advancing applications in hydrogen production, CO₂ conversion, methane reforming, polymer recycling, and photocatalysis, enabling data-centric materials discovery. At the system level, smart manufacturing has evolved into an intelligence-driven paradigm in which continuous data streams enable forecasting, optimization, and anomaly detection for self-adaptive production networks. Despite these advances, barriers such as implementation cost, cybersecurity risks, integration challenges, and skill shortages persist. Overall, the convergence of Industry 4.0, Green Chemistry, and data-driven catalysis is reshaping the chemical industry toward efficient, resilient, and sustainable systems, positioning chemical engineers as key drivers of digital and environmental innovation.*

Keywords: *smart manufacturing; chemical industry; green chemistry; artificial intelligence; machine learning; catalysis; sustainability; process optimization*

1. Introduction

The term *Industry 4.0* was introduced at the Hannover Fair in 2011 and was initially associated with Cyber-Physical Production Systems (CPPS), representing the application of Cyber-Physical Systems (CPS) concepts within manufacturing

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environments [1]. Over the following decade, Industry 4.0 significantly advanced the development of intelligent manufacturing by integrating technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Transformation (DT) [2]. A central objective of this transformation has been to minimize human involvement in production processes through increased automation and system optimization. The widespread adoption of automation and digital technologies under Industry 4.0 has not only reshaped manufacturing operations but has also extended its influence into related sectors and everyday life. The emergence of Industry 5.0 has shifted the focus of digital manufacturing toward sustainability, resilience, and human-centered design, creating new expectations for human-machine interaction (HMI) within human-centric smart manufacturing (HCSM). In manufacturing environments, HMI can generally be described through four stages: (1) sensing and hardware components that gather environmental and user-input information, (2) data processing systems that transform signals into meaningful data, (3) communication mechanisms that transfer data to processing units, and (4) interaction and collaboration between humans and machines. Among these stages, sensor technologies and data utilization have become critical areas for advancing HMI performance. This importance stems not only from ongoing technological innovations and emerging research but also from the influence of the human-centered principles introduced by Industry 5.0 [3].

2. Modern Chemical Engineering

Chemical engineering has traditionally been a fundamental driver of industrial progress, continually adapting to scientific advances and societal needs. In the current era, it operates at the intersection of two major paradigms: Industry 4.0, which represents the digital transformation of manufacturing systems, and Green Chemistry, which promotes environmentally responsible design of chemical products and processes. The convergence of these approaches within the framework of smart manufacturing enables the development of highly advanced and sustainable production systems, marking a shift toward more efficient and environmentally conscious industrial practices. Industry 4.0 incorporates a range of enabling technologies, including artificial intelligence (AI), the Internet of Things (IoT), robotics, big data analytics, cloud computing, and cyber-physical systems, all of which contribute to the integration of digital and physical manufacturing environments (Fig. 1). In chemical engineering applications, this transformation is reflected in smart manufacturing systems that connect equipment and processes through real-time data acquisition, advanced analytics, predictive maintenance, and simulation-based optimization. IoT-enabled sensors distributed across chemical plants continuously measure critical process variables such as temperature, pressure, and composition, generating continuous data

streams that support predictive modeling and early detection of process deviations. These data-driven approaches improve operational safety, efficiency, and flexibility while enabling chemical engineers to employ digital twins - high-fidelity virtual representations of physical systems to simulate, analyze, and optimize chemical processes without interrupting actual operations. This capability reduces experimental costs and risks while enhancing process performance, product yield, and responsiveness to market demands. In parallel, Green Chemistry provides a complementary framework focused on minimizing environmental impact by designing chemical processes that reduce or eliminate hazardous substances at their source rather than relying on downstream treatment (Fig 2). While chemists develop safer and more sustainable reaction pathways at the laboratory scale, chemical engineers play a critical role in scaling these innovations by applying principles of transport phenomena, reaction engineering, thermodynamics, and economic analysis. Together, these integrated approaches support the development of chemical manufacturing systems that are not only technologically advanced but also safer, more sustainable, and economically efficient [4].



Figure 1. Industry 4.0 in chemical engineering

2.1 Green Chemistry Principles and Their Integration with Industry 4.0 for Sustainable Chemical Manufacturing

The Twelve Principles of Green Chemistry, introduced by Paul Anastas and John Warner, provide a systematic framework for designing chemical processes that minimize pollution, reduce hazardous substance use, enhance energy efficiency, and promote the use of renewable resources. Unlike traditional end-of-pipe treatment approaches, Green Chemistry emphasizes pollution prevention at the molecular level through strategies such as waste minimization, atom economy,

safer reagents, and renewable feedstocks. This shift from reactive environmental management to proactive process design has led to improved environmental performance, regulatory compliance, and economic benefits via reduced raw material and energy consumption.

The integration of Green Chemistry with Industry 4.0 technologies establishes a synergistic framework for sustainable and intelligent chemical manufacturing. IoT-based sensors enable continuous monitoring of process conditions and rapid detection of inefficiencies, while artificial intelligence supports data-driven optimization of operating parameters to reduce emissions and resource use. Digital twin technologies further enhance sustainability by enabling virtual testing of greener reaction pathways and alternative materials prior to industrial implementation, thereby lowering experimental risk and cost.

At a broader level, Industry 4.0 enhances sustainability across supply chains through improved digital connectivity, traceability, and resource management, supporting circular economy practices and reduced carbon emissions. Industrial applications demonstrate that real-time data analytics and automation can significantly improve efficiency, safety, and environmental performance while maintaining economic viability. Overall, the convergence of smart manufacturing and Green Chemistry delivers substantial technical, environmental, and economic advantages, while also reshaping the role of chemical engineers toward more interdisciplinary, data-driven, and sustainability-focused responsibilities.

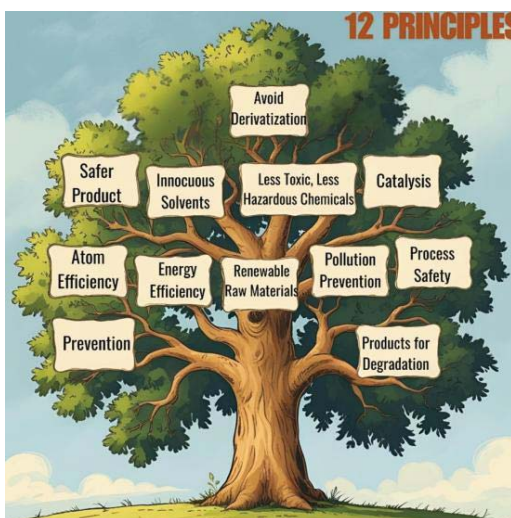


Figure 2. The 12 Principles of Green Chemistry for sustainable chemical design.

Building on this, the evolving role of chemical engineers demands continuous upskilling and adaptation, with increasing emphasis on data analytics, artificial

intelligence, process modeling, and sustainability-driven engineering within both academic curricula and industrial training programs. As digital and green technologies become further integrated, future chemical manufacturing systems are expected to progress toward fully autonomous and self-optimizing plants capable of real-time operational adjustment to maximize efficiency while minimizing environmental impact.

At a broader scale, industrial ecosystems are likely to adopt more collaborative, data-centric frameworks aligned with Industry 5.0 principles, prioritizing human-centric design, sustainability, and ethical responsibility in manufacturing. In parallel, regulatory structures are anticipated to evolve in response to these technological advances, facilitating faster and more structured adoption of smart and sustainable industrial practices. Within this context, chemical engineers will assume increasingly strategic roles, contributing not only technical expertise but also leadership in sustainability governance, digital transformation, and industrial innovation [5].



Figure 3. Framework for smart factory implementation in chemical plants [5].

The chemical manufacturing industry is experiencing a major shift driven by the widespread implementation of smart manufacturing and Industry 4.0 technologies. The deployment of digital systems such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, big data analytics, automation, and robotics has significantly enhanced operational performance by improving process stability, adaptability, and production efficiency (Figure 3). These technologies enable continuous monitoring of industrial operations, advanced data analysis, and automated control strategies that support optimized process conditions, reduced equipment failures, improved product consistency, and lower resource and energy consumption.

In addition, digital transformation strengthens supply chain integration by enabling real-time tracking of materials, inventory, and system performance, which improves coordination and increases resilience against disruptions. However, the implementation of such advanced systems is associated with several challenges, including high investment costs, cybersecurity risks, integration with existing infrastructure, and a shortage of multidisciplinary expertise combining chemical engineering and digital competencies. Addressing these limitations requires targeted investment in workforce development, interdisciplinary training, and strategic talent acquisition.

Overall, the adoption of smart technologies in chemical production not only enhances operational safety, efficiency, and resource management but also accelerates innovation in sustainable manufacturing practices. As industrial digitalization continues to advance, smart factories are expected to become a key driver of competitiveness and sustainability in the chemical sector, enabling companies to meet evolving economic, environmental, and regulatory demands [5].

2.2 Digital Transformation of the Chemical Industry

The chemical industry is experiencing a rapid and multidimensional transformation driven by the adoption of smart manufacturing within the Industry 4.0 framework. As a foundational supplier to sectors such as agriculture, pharmaceuticals, automotive, and construction, it operates under continuous pressure to enhance efficiency, adaptability, and competitiveness while simultaneously meeting increasingly stringent sustainability requirements.

In this context, smart manufacturing integrates advanced digital technologies—including the Internet of Things (IoT), artificial intelligence (AI), machine learning, computer vision, deep learning, and big data analytics—into production systems. This integration enables real-time monitoring, automated process control, and intelligent decision-making. As a result, manufacturers can achieve rapid data acquisition and advanced analytics-driven optimization of process parameters, improved resource utilization, and reduced operational inefficiencies. By reducing dependence on manual data handling and minimizing human error, these technologies significantly improve process reliability and productivity. In addition, AI-supported and automated systems enhance energy efficiency through optimized equipment operation while ensuring consistent product quality. Predictive maintenance strategies, enabled by advanced analytics, further allow early detection of equipment degradation, thereby reducing downtime and lowering maintenance costs. Moreover, data-driven insights into market trends and consumer preferences support continuous innovation and faster adaptation to evolving industrial demands. Collectively, these capabilities enhance production flexibility and strengthen responsiveness to dynamic market and operational

conditions. However, successful deployment depends on the integration of reliable sensing technologies, robust communication networks, and resilient digital infrastructure within existing industrial environments. Overall, smart manufacturing is emerging as a key enabler of sustainability, operational resilience, and long-term competitiveness in the chemical sector [6].

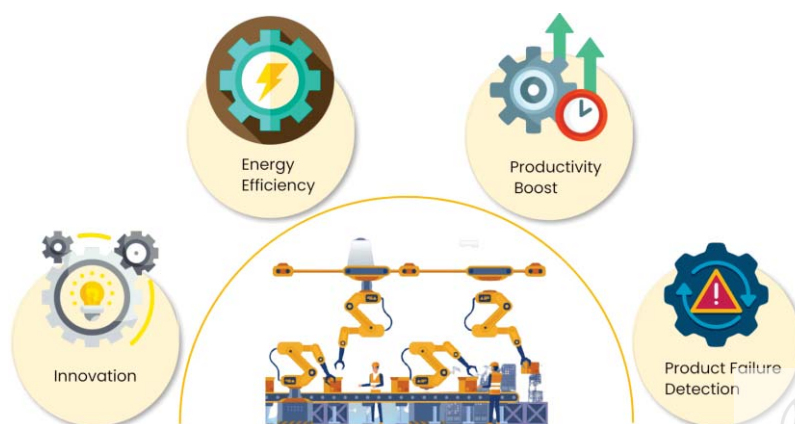


Figure 4. Smart manufacturing in the chemical industry enables productivity gains, energy efficiency, innovation, and early failure detection through AI- and IoT-driven systems.

Building upon these advancements, Industry 4.0 is also being widely implemented across chemical, pharmaceutical, and food production systems, where it enhances automation, process control, and operational intelligence. This results in improved process reliability, repeatability, supervision, fault detection, maintenance efficiency, and product quality (Figure 4). The effectiveness of such systems relies on the integration of high-performance industrial equipment with interconnected digital technologies capable of ensuring seamless data acquisition, integration, and centralized storage within unified platforms. Centralized monitoring systems provide real-time visibility of equipment status, support rapid fault diagnosis, and consolidate operational data for informed decision-making. Furthermore, these technologies improve process monitoring, streamline recipe management, and enable faster product transitions without disrupting ongoing production. As a result, Industry 4.0 adoption leads to enhanced productivity, reduced energy consumption, improved material handling, optimized asset utilization, and lower operational costs, thereby strengthening overall industrial performance [7].

While Industry 4.0 establishes the digital backbone of modern industrial systems through automation, connectivity, and data-driven control, its influence extends beyond manufacturing operations into scientific research and materials

innovation. In particular, the integration of artificial intelligence (AI), machine learning (ML), and computational modeling with experimental catalysis is reshaping the development of advanced materials and chemical processes.

Engineered heterogeneous catalysts, including supported metals, zeolites, defect-engineered structures, and multicomponent systems, exhibit enhanced activity, selectivity, and stability due to precisely controlled active sites and tailored porosity. Data-driven methodologies enable predictive modeling, high-throughput screening, mechanistic insight generation, and rational catalyst design by linking synthesis parameters, structural properties, and performance outcomes across multiple scales. These approaches are widely applied in areas such as carbon dioxide conversion, methane reforming, hydrogen production, polymer recycling, and photocatalysis, supported by digital platforms including PHOTOREAC, QMOF, and PhotoCatDB, which facilitate the transition from laboratory-scale research to industrial-scale applications. Furthermore, hybrid frameworks that combine mechanistic understanding with data-driven learning enhance interpretability, improve predictive accuracy, and optimize process performance. Collectively, these developments represent a shift toward data-centric catalysis, accelerating materials discovery, enabling sustainable chemical technologies, and reinforcing the essential role of human expertise in guiding responsible AI-driven innovation in chemical engineering [8].

Building on this digitally enabled and data-centric foundation, smart manufacturing is evolving toward more integrated, adaptive, and intelligence-driven systems. In this paradigm, sensing technologies, computational analytics, and adaptive control mechanisms operate synergistically to create continuous feedback loops that transform operational data into actionable process improvements.

Within this framework, modern production systems are designed to handle variability in demand, resource availability, and process conditions through dynamic reconfiguration and adaptive control strategies. Data collected from interconnected industrial assets is systematically processed (Fig. 5) to support forecasting, anomaly detection, and performance optimization at both equipment and system levels. This transition toward intelligence-driven manufacturing enables more precise coordination of operations, improved resource allocation, and enhanced stability across production networks.

As industrial systems become increasingly interconnected, emphasis is also shifting toward the integration of optimization models and quantitative decision-support tools that can further improve efficiency and sustainability. These approaches allow manufacturers to evaluate alternative production strategies, minimize operational costs, and ensure consistent product quality under varying conditions. In this way, digital manufacturing evolves into a more analytical and model-driven paradigm that complements existing advances in automation and industrial connectivity [9].



Figure 5. Data gathering and interpretation

Building on these system-level capabilities, the industrial impact of smart manufacturing is most evident in its large-scale adoption across key sectors. The chemical manufacturing industry, in particular, is undergoing a profound transformation driven by increasing demand, regulatory pressure, and global competition.

Within this context, smart manufacturing enables real-time process monitoring, predictive maintenance, automated quality control, improved safety management, and enhanced environmental compliance (Fig. 6).



Figure 6. Intelligent factory automation

AI-based systems analyze large volumes of operational data to optimize reaction conditions, detect anomalies, and improve process efficiency, thereby reducing

waste and operational costs. Meanwhile, IIoT technologies connect sensors, machines, and control systems, enabling continuous monitoring of energy consumption, emissions, and production parameters while supporting remote and automated operation.

Predictive maintenance improves operational reliability by enabling early detection of equipment failures, while smart safety systems reduce risks through real-time monitoring and automated emergency responses. In parallel, sustainability is strengthened through optimized resource utilization, reduced emissions, and the integration of greener feedstocks and chemical pathways.

Beyond production systems, digital technologies enhance supply chain resilience through demand forecasting, real-time logistics tracking, and improved inventory management. Emerging innovations such as digital twins, blockchain, augmented reality, and cloud computing further expand transparency, collaboration, and simulation capabilities. Despite these advancements, challenges such as high implementation costs, cybersecurity risks, workforce skill gaps, and legacy system integration remain significant barriers. Overall, the integration of smart technologies is reshaping the chemical industry toward a more efficient, safe, sustainable, and innovation-driven future [10].

Continuous feedback loops ensure that processes are constantly monitored and refined, enabling self-optimizing workflows that enhance efficiency, resilience, and responsiveness across the smart factory and its extended supply network.

3. Conclusions

The integration of Industry 4.0-enabled smart manufacturing with Green Chemistry represents a major shift in modern chemical engineering toward more intelligent and sustainable industrial systems. The deployment of advanced digital technologies, including artificial intelligence, machine learning, the Internet of Things, robotics, cloud computing, and big data analytics, has transformed industrial operations by enabling real-time monitoring, predictive maintenance, and data-driven process optimization. These developments have improved operational efficiency, safety, product quality, and resource utilization while simultaneously reducing downtime, energy consumption, and production costs.

When combined with Green Chemistry principles, this digital transformation enables the design of chemical processes that prioritize pollution prevention, resource efficiency, and the use of safer inputs from the outset. Environmental performance is increasingly addressed at the design stage rather than through corrective measures, leading to inherently cleaner production systems. In addition, enabling tools such as digital twins, IoT-based sensing, and AI-driven optimization enhance process understanding and support the development of more efficient and environmentally responsible chemical pathways. As a result,

sustainability and economic performance become complementary objectives within modern process design.

Across industrial applications such as catalysis and smart manufacturing systems, data-centric approaches are accelerating innovation, improving process control, and enabling more efficient and scalable production frameworks aligned with low-carbon and circular economy goals. Despite these advancements, challenges such as high implementation costs, cybersecurity risks, integration with legacy systems, and the need for advanced digital skills continue to limit widespread adoption.

Overall, this transformation is driving the chemical industry toward more autonomous, adaptive, and sustainable production systems, positioning chemical engineers as key contributors at the interface of digital innovation and environmental responsibility.

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