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Advancing circular economy in industrial chemistry and environmental engineering: Principles, alignment with United Nations sustainable development goals, and pathways to implementation

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ABSTRACT

This groundbreaking review explores the crucial role of the circular economy in industrial chemistry and environmental engineering. It surpasses a mere examination of principles and methods, delving into the profound significance and urgency of this transformative shift. By analyzing key elements such as resource efficiency, waste valorization, sustainable product design, industrial symbiosis, and policy integration, the study highlights the power of collaboration, technological advancements, and extensive literature research. It reveals the remarkable alignment between the circular economy and the Sustainable Development Goals (SDGs), emphasizing how circular practices promote resource efficiency, waste reduction, and sustainable production and consumption patterns, thus driving progress across multiple SDGs. With a specific focus on responsible consumption and production, clean energy, innovative industrial practices, climate action, ecosystem protection, water resource management, job creation, economic growth, sustainable urbanization, and collaboration, the review provides a comprehensive roadmap for adopting circularity. Its practical recommendations cover sustainable material selection, resource efficiency, closing loop, digitalization, and robust policy support. In addition, it emphasizes the paramount importance of collaboration, stakeholder engagement, education, capacity building, circular supply chain management, and effective policy frameworks in spearheading circular economy initiatives. Drawing inspiration from diverse circular economy models and compelling case studies in industrial chemistry, the study highlights the integration of environmental, social, and governance (ESG) factors, ensuring both sustainability and positive societal impact. This comprehensive review serves as a guiding light, demonstrating the immense potential of the circular economy in driving sustainable development. It offers actionable guidance for implementing circular practices, empowering professionals to make tangible contributions to a more sustainable future. Additionally, it serves as a foundational piece, fueling the advancement of knowledge, inspiring further research, and propelling remarkable progress in the ever-evolving fields of industrial chemistry and environmental engineering.

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1. Introduction

The circular economy is a concept that aims to redefine traditional linear economic models by promoting the reuse, recycling, and regeneration of resources. In the context of industrial chemistry and environmental engineering, the circular economy plays a crucial role in the transformation of traditional industrial practices into more sustainable and environmentally friendly processes [1]. Resource efficiency is one of the key principles of the circular economy and is to maximize resource efficiency. Industrial chemistry and environmental engineering can contribute to this goal by optimizing production processes to minimize waste generation and reduce resource consumption. By implementing cleaner production methods and recycling or reusing by-products, industries can minimize their environmental footprint and conserve natural resources. Waste Valorization and Recycling is one of the principles of circular economy. It encourages the valorization of waste materials by finding alternative uses or transforming them into valuable resources. Industrial chemistry and environmental engineering can play a crucial role in developing technologies and processes for waste treatment, such as recycling and upcycling, to convert waste materials into new products or feedstocks for industrial processes. This approach reduces the reliance on virgin resources and mitigates the environmental impacts of waste disposal [2].

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Figure 1. Circular economy model.

The principles of circular economy also emphasize the importance of designing products and processes with sustainability in mind. Industrial chemistry and environmental engineering can contribute by developing innovative materials, optimizing product lifecycles, and implementing eco-design strategies. By considering the entire life cycle of a product, from raw material extraction to end-of-life disposal industries can reduce environmental impacts and improve resource efficiency [3]. Figure 1 highlights the circular economy model.

Industrial symbiosis is a concept closely related to the circular economy, where different industries collaborate to exchange resources, by-products, or energy. This approach promotes resource efficiency and waste reduction by creating synergies between industries. Industrial chemistry and environ-mental engineering can facilitate the implementation of industrial symbiosis by identifying opportunities for collaboration and developing frameworks for resource exchange [4]. The circular economy encourages the adoption of sustainable chemical processes that minimize the use of hazardous substances and promote the use of renewable feedstocks. This includes the development of greener synthesis methods, the use of biobased materials, and the implementation of cleaner production technologies [5]. Life Cycle Assessment (LCA) is a tool widely used in environmental engineering to evaluate the environmental impacts of products and processes throughout their entire life cycle. LCA can help identify areas for improvement and guide decision-making towards more circular and sustainable solutions [6]. The circular economy is increasingly being integrated into environmental policies and regulations. Governments and regulatory bodies are promoting the adoption of the principles of circular economy in industrial sectors, setting targets for waste reduction, resource efficiency, and sustainable production [7].

This review paper encompasses a comprehensive exploration of the circular economy's role in industrial chemistry and environmental engineering. It delves into various aspects such as resource efficiency, waste valorization, sustainable product design, industrial symbiosis, and policy integration. The significance of this review article lies in its contribution to the existing knowledge gap. Surprisingly, no similar work has been done in the past, making this review a pioneering endeavor. By shedding light on the transformative power of the circular economy, this review paper provides valuable insight into the potential benefits and opportunities it offers. It goes beyond a mere overview of principles and methods, emphasizing the urgent need for a paradigm shift towards circularity. The paper underscores the importance of collaboration, technological advancements, and thorough literature survey in driving the circular economy. Furthermore, this review paper highlights the alignment between the circular economy and the Sustainable Development Goals (SDGs). By elucidating how circular practices can contribute to resource efficiency, waste reduction, and sustainable production and consumption patterns, the paper demonstrates the broader implications and positive impact of circularity across multiple SDGs. Overall, this review paper not only fills a significant knowledge gap but also provides actionable guidance for practitioners and policy makers to implement circular practices. It lays the groundwork for further research and advancements in the fields of industrial chemistry and environmental engineering. Its findings have the potential to drive sustainable development, promote responsible resource use, and contribute to a more sustainable and circular future.

Sustainable materials refer to materials that are sourced, produced, and utilized in a way that minimizes negative environmental impacts and supports long-term ecological balance [8,9]. Bio-based materials, derived from renewable resources such as plants, trees, or agricultural waste, align perfectly with this objective [10,11]. By utilizing bio-based materials, we reduce our reliance on non-renewable resources such as fossil fuels and minimize the associated environmental degradation and carbon emissions [12,13]. The use of bio-based materials also contributes to cleaner production practices [14,15]. The manufacturing processes for bio-based materials often require lower energy inputs and generate fewer harmful by-products compared to traditional materials derived from fossil fuels [16,17]. These processes can be more environmentally friendly, incorporating techniques such as bio-refining or fermentation, which have reduced carbon footprints and lower levels of pollution [18,19]. Cleaner production methods associated with bio-based materials help minimize waste, energy consumption, and harmful emissions, resulting in a more sustainable manufacturing approach [20,21]. Furthermore, the use of bio resources and bio-composites strengthens the sustainability and cleaner manufacturing theme. Bio resources, such as biomass or agricultural residues, offer a renewable and abundant source of raw materials for various industries [22,23]. These resources can be transformed into bio-composites, which are composite materials composed of a polymer matrix reinforced with natural fibers or particles derived from bio-based sources [24].

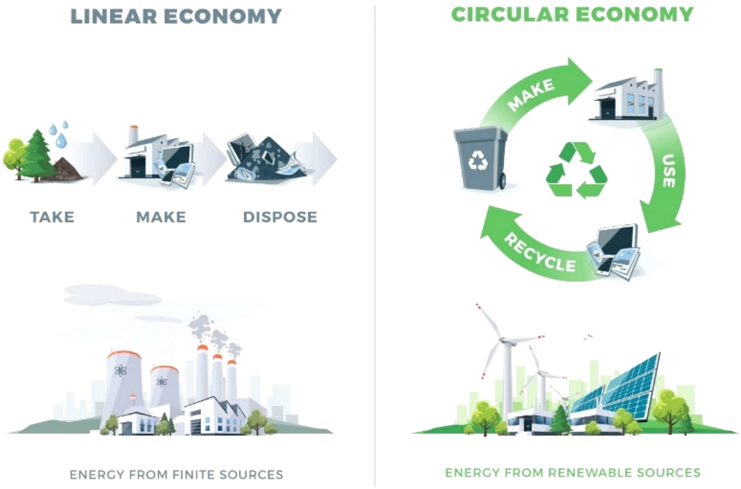


Figure 2. Linear economy *vs* the circular economy model.

Bio-composites possess desirable properties such as being lightweight, strength, and durability, while also being biodegradable or compostable. By utilizing bio resources and bio-composites, we enhance sustainability by reducing dependence on fossil-based materials, minimizing waste generation, and promoting circular economy principles.

2. Background

Various case studies and best practices highlight the successful implementation of circular economy principles in industrial chemistry and environmental engineering. These examples showcase real-world applications, innovative technologies, and successful business models that promote sustainable practices [25,26]. The circular economy emphasizes the importance of sustainable materials management, which involves reducing material consumption, optimizing material flow, and promoting resource recovery. This approach aims to minimize waste generation, extend the lifespan of materials, and create closed-loop systems [27]. Industrial ecology is a field that applies ecological principles to industrial systems, seeking to minimize waste, optimize resource use, and promote sustainability. It aligns closely with the circular economy and offers strategies and frameworks for designing and managing industrial processes in a more sustainable manner [28]. Figure 2 highlights the comparison between linear and circular economy models based on industrial chemistry and engineering.

Technological innovations play a crucial role in enabling the transition towards a circular economy in industrial chemistry and environmental engineering. These innovations include advanced recycling technologies, sustainable material development, process optimization techniques, and digital solutions that improve resource efficiency and promote circularity [29]. The circular economy requires collaboration and engagement among various stakeholders, including industry, policymakers, researchers, and consumers. Building partnerships and fostering cooperation among these stakeholders is essential for developing circular economy strategies, implementing sustainable practices, and driving systemic change [30]. Circular Economy in the Chemical Industry specifically focuses on the application of circular economy principles in the chemical industry. It discusses strategies for resource efficiency, waste reduction, and sustainable product design, highlighting the potential benefits and challenges of implementing circularity in this sector [31]. Circular Economy in Environmental Engineering explores the integration of the circular economy principles in the field of environmental engineering. It discusses how circularity can be applied in waste management, water treatment, and renewable energy systems, emphasizing the importance of resource recovery and sustainable infrastructure design [32].

Circular Economy and Sustainable Development Goals (SDGs) examines the linkages between the circular economy and the United Nations Sustainable Development Goals (SDGs). It discusses how circular economy strategies can contribute to achieving various SDGs related to sustainable production, responsible consumption, climate action, and resource conservation [33]. Circular Economy Business Models focus on circular economy business models in the context of industrial chemistry and environmental engineering. It explores different business strategies and models, such as product-as-a-service, sharing platforms, and closed-loop supply chains, that can enable the transition to a circular economy [34]. Circular Economy and Industrial Sectors examine the application of circular economy principles in specific industrial sectors, such as the automotive industry, electronics sector, and construction sector. It discusses strategies, challenges, and opportunities for implementing circularity in these sectors, highlighting the role of industrial chemistry and environmental engineering [35]. Circular Economy and Sustainable Supply Chains explores the role of circular economy principles in building sustainable supply chains. It discusses strategies for closing the material loop, reducing waste, and promoting resource efficiency across the supply chain, with a focus on the contribution of industrial chemistry and environmental engineering [36].

Circular Economy and Policy Frameworks discusses policy frameworks and initiatives that support the transition to a circular economy. It explores the role of governments, regulatory bodies, and international organizations in promoting circularity in industrial chemistry and environmental engineering, emphasizing the need for policy interventions and supportive measures [37].

3. Circular economy methods

Circular Economy and Innovation focuses on the role of innovation in driving the circular economy in industrial chemistry and environmental engineering. It discusses the importance of technological advancement, research and development, and collaboration between academia and industry in fostering circularity and sustainability [38]. There are several methods of circular economy in the context of industrial chemistry and environmental engineering.

Figure 3. Linear business models conversion strategies for circular economy.

Closed-Loop Systems and Material Recycling involve the recycling and reutilization of materials, allowing them to circulate within the economy rather than being disposed of as waste. This approach reduces the need for virgin resources and minimizes waste generation. Material recycling techniques such as mechanical recycling, chemical recycling, and thermal recycling can be employed to recover valuable materials from waste streams [39]. Product Life extension and Repair extends the lifespan of products through repair, refurbishment, and remanufacturing can significantly reduce waste and resource consumption. By promoting product durability, designing for disassembly and establishing repair networks, the circular economy aims to maximize the utility of products and minimize their environmental impact [40]. Biomimicry and Nature-Inspired Design draws inspiration from nature, and biomimicry and nature-inspired design approaches seek to develop innovative and sustainable solutions by emulating natural processes and systems. By applying these principles in industrial chemistry and environmental engineering, it is possible to create more efficient and sustainable processes, materials, and products [41]. Industrial Symbiosis and Resource Exchange involves establishing symbiotic relationships between different industries to exchange resources, by-products, and energy. This approach facilitates the efficient utilization of resources and promotes waste reduction. By identifying synergies and fostering collaboration, industrial symbiosis contributes to the circular economy and is explicitly shown in Figure 3 [42].

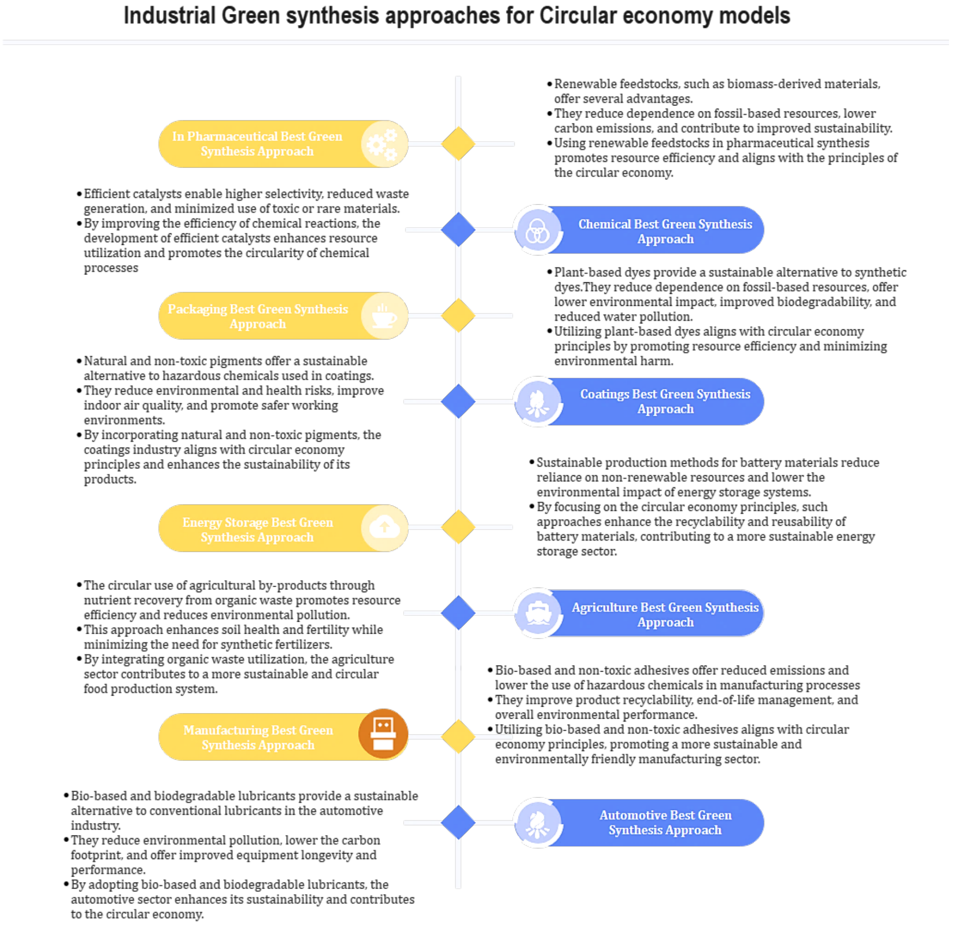
Green chemistry principles promote the design and development of chemical processes that minimize the use of hazardous substances, reduce waste generation, and increase energy efficiency. By adopting sustainable processes and using safer chemicals, industrial chemistry can contribute to the circular economy and reduce its environmental impact [5]. Industrial Upcycling and Repurposing involves transforming waste or by-products into new, higher-value materials or products. This approach promotes resource efficiency and reduces waste by finding alternative uses for materials that would otherwise be discarded [3].

Digital technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and data analytics, can be used to optimize industrial processes, resource management, and logistics. By collecting and analyzing data, companies can identify areas for improvement, improve resource efficiency, and reduce environmental impacts [43]. Product Service Systems (PSS) and sharing economy models shift the focus from selling products to providing services. Instead of owning products, consumers can access them as services, which can lead to reduced resource consumption and waste. PSS and sharing economy models encourage the durability, reparability, and efficient use of the product [44]. Eco-design principles involve considering the entire life cycle of a product, from raw material extraction to end-of-life disposal, and optimizing it for environmental performance. Sustainable product development practices aim to minimize environmental impacts, improve resource efficiency, and promote circularity [45]. Reverse logistics focuses on the management of product returns, remanufacturing, and recycling processes. Closed-loop supply chains integrate reverse logistics, allowing the recovery and reuse of materials, components, and products, thus reducing waste and optimizing resource utilization [46]. These methods provide further insights and applications of methods that can be employed in the context of industrial chemistry and environmental engineering to promote the circular economy. They explore specific techniques, technologies, and strategies that can contribute to resource efficiency, waste reduction, and sustainability in industrial processes.

4. Industrial Green synthesis approaches and role of green synthesis for circular economy

Green synthesis refers to the development of sustainable and environmentally friendly methods for producing chemicals, materials, and pharmaceuticals. It aims to minimize the use of hazardous substances, reduce energy consumption, and promote the efficient utilization of resources. Green synthesis plays a crucial role in the circular economy by aligning with its principles of resource efficiency, waste reduction, and sustainability.

During green synthesis focuses on developing sustainable processes that use environmentally benign solvents and reaction conditions. This approach reduces the environmental impact of chemical production, minimizes waste generation, and promotes the efficient use of resources [47]. Green synthesis promotes the use of renewable feedstocks, such as biomass-derived materials and agricultural residues, as alternatives to fossil-based resources. By utilizing renewable feedstocks, it reduces reliance on finite resources, lowers carbon emissions, and contributes to a more sustainable and circular economy [48]. Green synthesis focuses on the development of efficient catalysts and reaction optimization techniques that enhance selectivity, reduce waste, and minimize the use of toxic or rare materials. By improving the efficiency of chemical reactions, it reduces resource consumption and promotes the circularity of chemical processes. All detailed industrial approaches for green synthesis have been shown in Figure 4 [49].



- Renewable feedstocks, such as biomass-derived materials, offer several advantages.
- They reduce dependence on fossil-based resources, lower carbon emissions, and contribute to improved sustainability.
- Using renewable feedstocks in pharmaceutical synthesis promotes resource efficiency and aligns with the principles of the circular economy.

- Efficient catalysts enable higher selectivity, reduced waste generation, and minimized use of toxic or rare materials.
- By improving the efficiency of chemical reactions, the development of efficient catalysts enhances resource utilization and promotes the circularity of chemical processes

- Plant-based dyes provide a sustainable alternative to synthetic dyes.They reduce dependence on fossil-based resources, offer lower environmental impact, improved biodegradability, and reduced water pollution.
- Utilizing plant-based dyes aligns with circular economy principles by promoting resource efficiency and minimizing environmental harm.

- Natural and non-toxic pigments offer a sustainable alternative to hazardous chemicals used in coatings.
- They reduce environmental and health risks, improve indoor air quality, and promote safer working environments.
- By incorporating natural and non-toxic pigments, the coatings industry aligns with circular economy principles and enhances the sustainability of its products.

- Sustainable production methods for battery materials reduce reliance on non-renewable resources and lower the environmental impact of energy storage systems.
- By focusing on the circular economy principles, such approaches enhance the recyclability and reusability of battery materials, contributing to a more sustainable energy storage sector.

- The circular use of agricultural by-products through nutrient recovery from organic waste promotes resource efficiency and reduces environmental pollution.
- This approach enhances soil health and fertility while minimizing the need for synthetic fertilizers.
- By integrating organic waste utilization, the agriculture sector contributes to a more sustainable and circular food production system.

- Bio-based and non-toxic adhesives offer reduced emissions and lower the use of hazardous chemicals in manufacturing processes
- They improve product recyclability, end-of-life management, and overall environmental performance.
- Utilizing bio-based and non-toxic adhesives aligns with circular economy principles, promoting a more sustainable and environmentally friendly manufacturing sector.

- Bio-based and biodegradable lubricants provide a sustainable alternative to conventional lubricants in the automotive industry.
- They reduce environmental pollution, lower the carbon footprint, and offer improved equipment longevity and performance.
- By adopting bio-based and biodegradable lubricants, the automotive sector enhances its sustainability and contributes to the circular economy.

Figure 4. Industrial chemistry green synthesis approaches for different sectors.

Green synthesis incorporates bio-catalysis, which utilizes enzymes and microorganisms, as a sustainable alternative to traditional chemical processes. Bio-catalysis offers high selectivity, mild reaction conditions, and reduced energy requirements, thus contributing to the circular economy and environmental sustainability [50]. Green synthesis considers the environmental impact of the entire life cycle of a product, from the extraction of raw materials to the disposal. Life cycle assessment (LCA) methods are used to evaluate the environmental footprint and identify opportunities to improve the sustainability and circularity of chemical processes [51].

These green synthesis implications provide insight into the role of green synthesis for the circular economy in industrial chemistry and environmental engineering. It highlights the importance of sustainable processes, renewable feedstocks, catalysts, bio catalysis, and life cycle assessment in promoting resource efficiency and reducing the environmental impact of chemical production. Table 1 presents industrial case studies that highlight the role of green synthesis for the circular economy.

5. Role of computational chemistry digital tools for promoting circular economy

The role of digital tools in promoting the circular economy in the context of industrial chemistry and environmental engineering is significant. Digital tools, such as data analytics, modeling, simulation, and monitoring systems, play a crucial role in optimizing processes, reducing waste, improving resource efficiency, and facilitating the transition to a circular economy. They enable better decision making, improved material flow management, and the development of innovative solutions. There are multiple specific roles of digital tools like IoT-enabled sensors for real-time monitoring of resource consumption and waste generation [67]. In process optimization, digital tools help optimize industrial processes by analyzing data, identifying inefficiencies, and suggesting improvements. They enable the implementation of cleaner production techniques and the reduction of resource consumption and waste generation. While the Material Traceability and Tracking Relics Digital tools facilitate the tracking and tracing of materials throughout their lifecycle. This promotes transparency, allows for better management of material flows, and supports the integration of recycled or reused materials into production processes. Block chain-based platforms for the traceability and certification of sustainable and circular products [68]. Figure 5 highlights the digital solution of the circular economy model for advance Lifecycle Assessment using digital tools to aid in conducting lifecycle assessments (LCAs) for evaluating the environmental impact of products or processes. LCAs help identify opportunities for improvement, identify hotspots, and support decision-making toward more sustainable and circular practices. Life cycle assessment (LCA) software for evaluating the environmental impact of products and processes [69].

Supply Chain Management digital tools enhance supply chain management by improving communication, collaboration, and coordination among stakeholders. They enable real-time data sharing, inventory management, and optimization of transportation and logistics, leading to reduced waste, improved resource utilization, and improved circularity.

Table 1. Case studies of industrial sector based on green synthesis approaches with key benefits.

Case study	**Industrial sector**	**Green synthesis approach**	**Key benefits**	**Reference**
Pharmaceutical APIs	Pharmaceutical	Use of renewable feedstock	-Reduced dependence on fossil-based resources -Minimized carbon emissions -Reduced environmental impact -Improved sustainability	[48]
Catalytic processes	Chemical	Development of efficient catalysts	-Higher selectivity and reduced waste generation -Minimized use of toxic or rare materials -Enhanced resource efficiency	[49]
Bioplastics	Polymer	Utilization of renewable feed stocks	-Reduced reliance on fossil-based plastics -Lower carbon footprint -Increased circularity of plastic production -Improved waste management	[52]
Waste-to-energy	Environmental Engineering	Biocatalysts and enzyme engineering	-Enhanced energy recovery from waste -Reduced environmental pollution -Improved resource utilization -Sustainable waste management	[53]
Bio-based plastics	Packaging	Use of renewable feedstock	-Reduced reliance on fossil-based plastics -Lower carbon emissions -Enhanced resource efficiency -Improved waste management	[54]
Green solvents	Chemical	Development of sustainable solvents	-Reduced environmental impact -Lower toxicity -Enhanced worker safety -Improved process sustainability	[55]
Sustainable fuels	Energy	Biomass conversion into biofuels	-Lower carbon emissions -Renewable energy source -Reduced dependence on fossil fuels -Circular use of agricultural waste	[56]
Green nanomaterials	Electronics	Green synthesis of nanomaterials	-Reduced environmental impact -Lower toxicity -Enhanced material efficiency -Reduced resource consumption -Improved product recyclability	[57]
Green dyes	Textile	Use of plant-based dyes	-Reduced dependence on synthetic dyes -Lower environmental impact -Improved biodegradability -Reduced water pollution	[58]
Eco-friendly cosmetics	Personal Care	Sustainable extraction of natural ingredients	-Reduced environmental impact -Avoidance of harmful chemicals -Support for biodiversity and local communities -Enhanced product sustainability	[59]
Green catalysis	Chemical	Use of renewable catalysts	-Reduced use of toxic metals -Lower energy consumption -Increased product selectivity -Improved recycling and reusability	[60]
Sustainable building materials	Construction	Use of recycled and bio-based materials	-Reduced reliance on virgin materials -Lower carbon emissions -Enhanced resource efficiency -Reduced waste generation	[61]
Green battery materials	Energy Storage	Sustainable production of battery materials	-Reduced reliance on non-renewable resources -Lower environmental impact -Improved recyclability and reusability of batteries	[62]
Sustainable paints	Coatings	Use of natural and non-toxic pigments	-Reduced use of hazardous chemicals -Lower environmental and health risks -Enhanced indoor air quality	[63]
Green fertilizers	Agriculture	Utilization of organic waste for nutrient recovery	-Circular use of agricultural by-products -Reduced environmental pollution -Enhanced soil health and fertility	[64]
Sustainable adhesives	Manufacturing	Development of bio-based and non-toxic adhesives	-Lower emissions and reduced use of hazardous chemicals -Improved product recyclability and end-of-life management -Reduced environmental impact and human health risks	[65]
Green lubricants	Automotive	Use of bio-based and biodegradable lubricants	-Reduced environmental pollution and toxicity -Lower carbon footprint and resource consumption -Enhanced equipment longevity and performance	[66]

The product design and manufacturing digital tools support sustainable product design by enabling virtual prototyping, simulation, and optimization. They help to create products that are easier to recycle, repair, or remanufacture, thus prolonging their useful life and reducing waste generation. Digital Marketplaces and Sharing Platforms facilitate the exchange, sharing, and reuse of resources, products, and services. They enable the creation of circular business models, such as product-as-a-service, sharing, economy platforms, and online marketplaces for used or refurbished products. Digital platforms for sharing and renting resources, such as machinery, equipment, or office space [70]. Digital marketplaces for buying and selling used or refurbished products [71].

Data Analytics and Artificial Intelligence (AI) Digital tools harness the power of data analytics and artificial intelligence to extract insights, identify patterns, and optimize processes. They enable predictive maintenance, energy optimization, and intelligent decision-making, leading to improved resource efficiency and reduced environmental impact.

Table 2. Highlights the digital tools with their roles, functions and benefits.

Digital tool	Role and function	Benefits	Reference
IoT-enabled sensors	Real-time monitoring of resource consumption and waste generation	-Optimization of resource utilization -Identification of inefficiencies and waste reduction -Data-driven decision-making for process optimization	[74]
Blockchain-based platforms	Traceability and certification of sustainable and circular products	-Transparency and trust in supply chains -Authentication of product origin and quality -Enhanced circularity and reduced risks of counterfeit or non-compliant products	[75]
Life cycle assessment (LCA)	Evaluation of environmental impact of products and processes	-Identification of environmental hotspots and improvement opportunities -Support for sustainable product design and decision-making -Enhanced understanding of product lifecycle and circularity	[76]
Digital marketplaces	Sharing and renting resources, such as machinery, equipment, or office space	-Improved resource utilization and reduced idle capacity -Access to shared resources and services for circular business models -Promotion of collaborative consumption and reduced waste generation	[77]
Digital platforms	Buying and selling used or refurbished products	-Extended product lifespan and reduced waste -Creation of secondary markets for circular products -Increased accessibility to affordable, sustainable options	[71]
AI and machine learning	Optimization of production processes, waste reduction, and energy efficiency	-Improved process efficiency and reduced resource consumption -Real-time monitoring and predictive maintenance for enhanced sustainability -Identification of patterns and insights for circular economy strategies	[78]
Consumer engagement apps	Mobile apps for recycling guidance, sustainability information, and product traceability	-Education and engagement of consumers in circular practices -Increased awareness and involvement in recycling and sustainable choices -Transparency and information on product lifecycle and sustainability	[79]
Digital twin	Virtual replica of physical systems or processes for monitoring, analysis, and optimization	-Real-time monitoring and optimization of resource utilization -Improved operational efficiency and reduced waste -Enhanced predictive maintenance and reduced downtime	[80]
Big data analytics	Analysis of large datasets to extract insights, identify patterns, and optimize processes	-Identification of opportunities for waste reduction and resource efficiency -Data-driven decision-making for circular economy strategies -Improved forecasting and planning for better resource management	[81]
Virtual reality (VR)	Immersive technology for visualization, design, and simulation of circular processes	-Enhanced product design and prototyping for recyclability and reusability -Evaluation of material flows and process efficiency in a virtual environment -Improved stakeholder communication and engagement in circular initiatives	[82]
Cloud computing	On-demand access to shared computing resources and storage for data analysis and collaboration	-Scalability and cost-effectiveness for implementing circular economy solutions -Enables real-time monitoring and decision-making based on cloud-based analytics -Facilitates collaboration and data sharing among stakeholders	[83]
Augmented reality (AR)	Overlaying digital information onto the physical environment for enhanced visualization	-Assistance in waste sorting and recycling processes -Real-time guidance for resource optimization and process efficiency -Education and training for circular practices and sustainability	[84]
Robotics and automation	Automated systems and robots for improved resource efficiency and waste reduction	-Efficient material handling and sorting for recycling processes -Enhanced precision and accuracy in manufacturing processes for circular products -Reduced human error and improved safety in resource management	[85]
3D printing	Additive manufacturing technology for customized production and reduced material waste	-On-demand production and localized manufacturing for reduced transportation impacts -Optimization of material usage and reduced scrap during manufacturing -Enables design for repair and remanufacturing, prolonging product lifespan	[86]

Figure 5. Digital circular economy eco-system for industrial green synthesis.

Consumer Engagement and Education Digital tools help educate and engage consumers in the circular economy. They enable information sharing, product traceability, and consumer involvement in recycling or repurposing initiatives, fostering a culture of sustainability and circularity. AI and machine learning algorithms incorporate for optimizing production processes, waste reduction, and energy efficiency [72], while digital platforms for consumer engagement, such as mobile apps for recycling guidance or sustainability information [73]. Table 2 highlights the digital tools with their roles, functions, and benefits.

Figure 6. Role of each SDG's for green synthesis in circular economy model.

6. Role of SDG's efforts of circular economy and green synthesis industrial chemistry

The Sustainable Development Goals (SDGs) provide a framework for addressing global challenges and promoting sustainable development. The efforts to achieve the SDGs align closely with the principles and goals of the circular economy in the context of industrial chemistry and environmental engineering. The circular economy contributes to several SDGs by promoting resource efficiency, reducing waste and pollution, and promotion sustainable production and consumption patterns. SDG 12: Responsible Consumption and Production. The circular economy promotes sustainable production processes, resource efficiency, and waste reduction, contributing to SDG 12 [87]. By implementing circular practices, such as recycling, reusing, and remanufacturing, the industrial sector can minimize resource extraction and waste generation [88]. Figure 6 shows the role of each SDG's for green synthesis in the circular economy model. The circular economy promotes energy efficiency and the use of renewable energy sources, contributing to SDG 7 [87]. Industrial chemistry and environmental engineering can leverage circular approaches to optimize energy use, reduce emissions, and transition to clean energy technologies [89]. The circular economy fosters innovation, technological advancements, and sustainable industrial practices, supporting SDG 9 [90]. Industrial chemistry and environmental engineering play a key role in developing and implementing circular solutions, such as eco-design, green chemistry, and sustainable infrastructure [91]. The circular economy contributes to climate action by reducing greenhouse gas emissions, minimizing waste, and promoting sustainable resource management. Industrial chemistry and environmental engineering can adopt circular practices to mitigate climate change impacts and promote a low-carbon economy [92]. The circular economy helps protect marine and terrestrial ecosystems by reducing pollution, conserving resources, and promoting sustainable land and water management [93]. Industrial chemistry and environmental engineering can contribute to these goals by implementing circular approaches that minimize environmental impacts and promote biodiversity conservation [94].

The circular economy promotes efficient water use, wastewater treatment, and water resource management, contributing to SDG 6 [93]. Industrial chemistry and environmental engineering can implement circular practices that minimize water consumption, recycle water, and improve water quality [94]. The circular economy offers opportunities for job creation, innovation, and sustainable economic growth, supporting SDG 8 [93]. Industrial chemistry and environmental engineering can drive the transition to a circular economy, generating new green jobs and fostering economic resilience [92]. The circular economy promotes sustainable urbanization, resource efficiency, and waste reduction, aligning with SDG 11 [95]. Industrial chemistry and environmental engineering can contribute to sustainable cities by implementing circular practices in waste management, infrastructure design, and urban planning [91]. The circular economy requires collaboration and partnerships across sectors and stakeholders, supporting SDG 17 [96]. Industrial chemistry and environmental engineering can collaborate with policymakers, companies, and communities to drive circular initiatives and achieve sustainable development goals [97].

7. Strategies and Industrial practices efforts for promoting the circular economy

The transition towards a more sustainable and circular economy requires the implementation of various strategies and practices across different sectors. This article highlights key areas that contribute to achieving circularity in industrial processes and supply chains. These areas include sustainable material selection, resource efficiency and waste reduction, closing the loop, digitalization and Industry 4.0, policy and regulatory support, collaboration and stakeholder engagement, circular supply chain management, education and capacity building, and policy and regulatory frameworks. Promoting sustainable material selection is crucial in fostering environmentally friendly industrial processes. By advocating for the use of renewable and recyclable materials, industries can reduce their reliance on nonrenewable resources and minimize the negative impact on natural ecosystems. Embracing green chemistry principles further minimizes the use of hazardous substances, contributing to a safer and cleaner future. Resource efficiency and waste reduction play a significant role in sustainable industrial practices. By adopting cleaner production techniques and industrial symbiosis practices, industries can optimize resource use, minimize waste generation, and maximize resource utilization. Integrating waste valorization techniques such as recycling, reprocessing, and energy recovery further contribute to waste reduction and resource maximization. Details of each strategy and practice are given below.

Figure 7. Industrial growth based on green synthesis circular economy model.

7.1. Sustainable material selection

Promoting sustainable material selection is essential for fostering environmentally friendly industrial processes. One way to achieve this is by advocating for the use of renewable and recyclable materials [29]. By opting for such materials, industries can reduce their reliance on nonrenewable resources and contribute to the conservation of natural ecosystems. Furthermore, the adoption of principles of green chemistry plays a crucial role in minimizing the use of hazardous substances [5]. This approach focuses on developing and utilizing chemical processes that are less harmful to the environment and human health. By prioritizing green chemistry, industries can mitigate the negative impacts associated with toxic chemicals and contribute to a safer and cleaner future. Another important aspect of sustainable material selection is the implementation of eco-design approaches [97]. This involves considering the entire lifecycle of products, from their creation to their eventual disposal or reuse. By incorporating eco-design principles, industries can ensure that products are designed with recyclability and reusability in mind. This not only reduces waste generation, but also enables the extraction of valuable resources from discarded products, minimizing the need for new raw materials.

Sustainable material selection encompasses various strategies that aim to minimize the environmental footprint of industrial processes. Promoting the use of renewable and recyclable materials, adopting green chemistry principles, and implementing eco-design approaches are all crucial steps toward achieving a more sustainable and circular economy. By embracing these practices, industries can contribute to resource conservation, pollution reduction, and overall well-being of the planet.

7.2. Resource efficiency and waste reduction

Achieving resource efficiency and waste reduction is crucial for sustainable industrial practices. Industries can optimize resource use and minimize waste generation by implementing cleaner production techniques. These techniques involve adopting advanced technologies and efficient processes to reduce resource consumption while maintaining or increasing productivity. By doing so, industries can contribute to environmental preservation, cost-effectiveness, and long-term competitiveness.

Another effective approach to resource efficiency is the adoption of industrial symbiosis practices. This involves the exchange of resources and by-products among different industries [98]. By identifying opportunities for collaboration and resource sharing, industries can minimize waste generation and maximize resource utilization. For example, one industry's by-product can serve as a valuable resource for another industry, reducing the need for virgin materials and promoting a circular economy. Integrating waste valorization techniques is also crucial for waste reduction and resource maximization. Techniques such as recycling, reprocessing, and energy recovery play a significant role in this regard and shown in Figure 7 [98]. Recycling involves collecting and processing waste materials to create new products or raw materials. Reprocessing focuses on recovering valuable components from waste or transforming them into usable materials. Energy recovery harnesses the energy content of waste through methods like incineration or anaerobic digestion [99]. These techniques not only minimize waste sent to landfills but also conserve resources and reduce the environmental impact of waste disposal.

Prioritization of resource efficiency and waste reduction is essential for sustainable industrial practices. Implementing cleaner production techniques, adopting industrial symbiosis practices, and integrating waste valorization techniques contribute to a more sustainable and circular economy. By optimizing resource use, minimizing waste generation, and maximizing resource recovery, industries can significantly reduce their environmental footprint and pave the way toward a more sustainable future.

7.3. Closing the loop

Closing the loop is a crucial aspect of achieving a circular economy. To accomplish this, various strategies can be employed. Encouraging product take-back systems and facilitating recycling and remanufacturing processes are effective approaches [100]. By establishing mechanisms for customers to return products at the end of their life cycle, materials can be recovered and reused. This promotes resource conservation and minimizes waste. Additionally, developing innovative business models, such as product-as-a-service and sharing economy platforms, can contribute to closing the loop [34]. These models prioritize access to products and services rather than ownership, promote sharing, and reduce the overall demand for new products. Lastly, promoting extended producer responsibility and implementing reverse logistics are essential steps [101]. By holding producers accountable for the entire life cycle of their products, including their end-of-life disposal, they are incentivized to design products that are easier to recycle and ensure their proper management. Implementing reverse logistics systems enables the efficient collection and transportation of used products or materials back to manufacturers for recycling or remanufacturing. Together, these measures play a significant role in closing the loop, fostering a more sustainable and circular economy.

7.4. Digitalization and Industry 4.0

Digitalization and Industry 4.0 bring forth significant advancements by harnessing digital technologies such as IoT, big data analytics, and artificial intelligence. These technologies enable industries to optimize resources and improve process efficiency, leading to improved productivity [42]. Digital twins and simulation tools play a vital role in this transformation, allowing businesses to model and optimize production processses, thereby reducing waste. Furthermore, block chain technology offers valuable solutions for traceability, transparency, and circular supply chain management. By leveraging the block chain, industries can ensure the authenticity of products, enhance trust among supply chain partners, and promote sustainability [79]. In general, digitalization and Industry 4.0 enable businesses to achieve resource optimization, process efficiency, and simplified supply chain operations [97].

7.5. Policy and regulatory support & collaboration and stakeholder engagement

Policy and Regulatory Support Implementing supportive policies, incentives and regulations to drive circular economy practices [101], encouraging collaboration among stakeholders, and facilitating knowledge exchange through networks and platforms [29,102]. In addition to it, conducting research and development to drive innovation in circular economy technologies and practices [98]. Encouraging collaboration among industry, academia, government, and civil society to foster knowledge sharing, innovation, and implementation of circular economy principles. Engaging stakeholders through multi-stakeholder platforms, partnerships, and dialogues to drive systemic change and collective action [30]. Facilitating cross-sectoral collaboration to identify synergies, exchange best practices, and develop circular economy solutions [103].

7.6. Circular supply chain management, education and capacity building

Promoting education and awareness programs is crucial for enhancing understanding of circular economy concepts and fostering skills for sustainable development. It is essential to incorporate circular economy principles into curricula and training programs for professionals in industrial chemistry and environmental engineering. By doing so, we can ensure that future leaders in these fields are equipped with the knowledge and expertise to drive circularity in their industries. Furthermore, supporting research and knowledge dissemination on circular economy topics through academic institutions and research centers is essential. This enables the development of innovative solutions and the sharing of best practices for implementing circular economy principles effectively [29,104,105].

In order to advance circularity in supply chains, it is important to implement circular procurement practices. This involves prioritizing the use of recycled, recyclable, and environmentally friendly materials in the sourcing and production processes. By adopting such practices, we can reduce waste generation and promote the use of sustainable resources. Furthermore, adopting supply chain transparency and traceability tools is crucial to ensure ethical sourcing, sustainable production, and circularity of products. These tools enable companies to monitor and track the origin of materials, their environmental impact, and the conditions under which they are produced. This information empowers consumers and businesses to make informed choices and supports the shift towards more sustainable and circular practices. Moreover, promoting the integration of circular economy principles in logistics and distribution processes is vital. This includes implementing reverse logistics for product recovery and recycling. By establishing efficient systems for collecting, refurbishing and repurposing products at the end of their lifecycle, we can minimize waste and maximize the value of resources [99,106].

7.7. Policy and regulatory frameworks

In order to foster the transition towards a more sustainable and circular economy, various strategies can be implemented. One key aspect is the development of supportive policies, regulations, and incentives that promote the adoption of circular economy practices within the industrial sectors [107]. These measures can help create an enabling environment for businesses to embrace circularity by providing guidance, financial support, and regulatory frameworks that encourage resource efficiency, waste reduction, and integration of circular principles into production and consumption systems. Another effective approach is the establishment of extended producer responsibility frameworks, which shift the burden of product lifecycle management from consumers to manufacturers. By implementing such frameworks, manufacturers are incentivized to design products for durability, reparability, and recyclability. This encourages the production of goods that can be easily disassembled, repaired, or recycled, reducing waste generation and extending the lifespan of products [107,108].

Furthermore, it is crucial to encourage the development of circular economy indicators and metrics that can effectively monitor progress and guide policy making [108]. These indicators provide valuable insights into the environmental, social, and economic impacts of circular economy initiatives, allowing policymakers to assess the effectiveness of their strategies and make informed decisions. By having reliable data and metrics, policymakers can tailor their approaches, identify areas of improvement, and track the overall transition towards a circular economy.

The promotion of supportive policies, the establishment of extended producer responsibility frameworks, and the development of circular economy indicators and metrics are essential elements in advancing the adoption of circular economy practices. By implementing these measures, governments, businesses, and society as a whole can work together to create a more sustainable and resilient future.

8. ESG & Industrial chemistry case studies role for novel circular economy model

Environmental, Social, and Governance (ESG) factors play a crucial role in shaping and implementing a novel circular economy model. ESG considerations are integral in guiding the principles, strategies, and practices of a circular economy to ensure its sustainability and positive social impact. From an environmental perspective, ESG factors help identify and address the ecological challenges associated with the circular economy.

Table 3. Sustainable ESG Metrices for Industrial Green Synthesis.

Sustainability metric	Description	Mathematical formula
Material efficiency	Measures the efficiency of resource utilization in production	Material Efficiency = (Output Mass / Input Mass) * 100%
Energy efficiency	Measures the efficiency of energy use in production processes	Energy Efficiency = (Output Energy / Input Energy) * 100%
Carbon footprint	Measures the greenhouse gas emissions associated with a product or process	Carbon Footprint = GHG Emissions (CO_2e)
Water footprint	Measures the water consumption and water pollution associated with a product or process	Water Footprint = Total Water Consumption or Pollution (liters)
Waste generation	Measures the amount of waste generated during production processes	Waste Generation = Amount of Waste Generated (metric tons)
Recycling rate	Measures the percentage of materials that are recycled or reused	Recycling Rate = (Recycled Materials / Total Materials) * 100%
Reutilization rate	Measures the percentage of products or components that are reused or repurposed	Reutilization Rate = (Reused Products / Total Products) * 100%
Life cycle assessment (LCA)	Evaluates the environmental impacts of a product or process throughout its life cycle	LCA = Sum of impacts across life cycle stages (e.g., extraction, production, use, disposal)
Circular economy index	Provides an overall measure of the circularity of an industrial system	Circular Economy Index = (Value of Circular Activities / Total Economic Value) * 100%

ESG frameworks provide a comprehensive approach to assess and mitigate environmental risks and impacts of circular economy practices [109,110]. This includes evaluating the use of resources, energy consumption, waste generation, and pollution. By integrating ESG principles into the circular economy model, businesses and policy makers can prioritize environmental conservation, climate action, and the presservation of natural resources.

In the context of industrial chemistry and environmental engineering, several novel circular economy models have emerged, each offering unique approaches to sustainable resource management and waste reduction [111,112]. One such model is the Cradle-to-Cradle (C2C) framework, which focuses on creating a regenerative and waste-free system by designing products and processes that emulate nature's cycles [113]. The C2C model encompasses key aspects such as material health, material reutilization, renewable energy, water stewardship, and social fairness. By adopting the C2C model, the industrial chemistry and environmental engineering sectors can transition towards a circular economy by reimagining their products, processes and systems. This model challenges the traditional linear approach of 'take-make-dispose' and emphasizes the importance of product design, material assessment, closed-loop systems, collaboration, and partnerships, as well as certification and standards [114,115]. These elements form a comprehensive framework that enables the integration of sustainable and circular practices throughout the value chain.

Another notable circular economy model is industrial symbiosis, which promotes resource optimization and waste reduction through collaboration between industries. By identifying opportunities for waste or by-products from one company to serve as valuable inputs for another, industrial symbiosis creates a closed-loop system that minimizes waste generation and maximizes resource utilization [116,117]. A well-known example is the Kalundborg Industrial Symbiosis in Denmark, where multiple companies interconnect their operations to achieve significant resource efficiency gains. Product-as-a-Service (PaaS) is a business model that shifts the focus from product ownership to product usage. By providing products as services, manufacturers retain the responsibility for maintenance, repair, and end-of-life management. This model encourages the design of durable, repairable, and upgradable products, promoting resource efficiency and effective resource recovery [118,119]. Philips Lighting (now Signify) has successfully embraced the PaaS model with its 'Light as a Service' offering, leading to energy savings, improved performance, and material recovery. Drawing inspiration from nature, biomimicry is a circular economy model that emulates natural design principles and processes. By observing and replicating nature's patterns, strategies, and systems, biomimicry enables the development of sustainable and resource-efficient solutions. The Lotus Effect, which inspired the creation of self-cleaning and water-repellent materials, serves as a prime example of how biomimicry can drive innovation across various industries. Collaborative consumption, also known as the sharing economy, is a circular economy model that promotes the sharing, renting, and collaborative use of resources [120,121]. By leveraging digital platforms and networks, collaborative consumption optimizes the utilization of underutilized assets and reduces the need for new production, thus minimizing waste. Airbnb exemplifies this model, allowing individuals to rent out their properties, maximizing the use of existing housing stocks and reducing the environmental impact associated with new construction.

In industrial ecology, it takes inspiration from natural ecosystems to design industrial systems that mimic nature's interconnectedness and resource efficiency [122]. By fostering collaboration among industries and stakeholders, industrial ecology optimizes resource flow and minimizes environmental impacts. The Kalundborg Eco-Industrial Park in Denmark stands as a prominent example, where multiple companies integrate their operations and create symbiotic relationships to achieve substantial resource conservation and waste reduction. Through the adoption of these novel circular economy models, industrial chemistry and environmental engineering can drive the transition toward a more sustainable and circular future. By embracing principles such as regenerative design, resource optimization, collaborative networks, and nature-inspired solutions, these models offer pathways to achieve a more efficient, resilient, and environmentally friendly industrial sector [123]. Table 3 is the representation of novel circular economy sustainability metrics along with their mathematical formulas in the context of industrial chemistry and environmental engineering.

By considering ESG factors in the implementation of circular economy models, the industrial chemistry and environmental engineering sectors can drive positive social change, promote sustainable consumption patterns, and foster inclusive and resilient communities.

Environmental factors play a crucial role in the circular economy, with a focus on minimizing environmental impacts and promoting sustainability. In the industrial chemistry and environmental engineering sectors, ESG considerations are integrated into the design and implementation of processes, products, and systems. Circular economy models offer a framework for achieving these goals by prioritizing resource efficiency, waste reduction, and environmental preservation. By adopting circular economy models, these sectors can effectively reduce resource consumption, minimize waste generation, and mitigate environmental pollution. This includes promoting efficient resource use to minimize the extraction and depletion of finite resources, implementing strategies such as recycling and remanufacturing to minimize waste, and adopting

Figure 8. C2C design framework along with industrial symbiosis case studies.

cleaner production processes and sustainable chemistry practices to mitigate pollution [37]. Additionally, circular economy models encourage the promotion of ecosystem resilience by emulating nature's regenerative processes through approaches like biomimicry and industrial symbiosis. This involves designing products and processes that mimic natural systems, optimizing resource flows, and fostering collaboration among industries. Lastly, circular economy models encourage sustainable innovation by driving the development of sustainable technologies, materials, and business models. By embracing concepts such as Product-as-a-Service and collaborative consumption, these sectors can promote resource efficiency, encourage product longevity, and foster a more sustainable and circular economy.

Social factors play a significant role in the implementation of circular economy models within the industrial chemistry and environmental engineering sectors. These models have a direct impact on workers, local communities, and stakeholders, promoting positive social outcomes. By adopting circular economy initiatives, these sectors can foster various social benefits.

i. *Job creation*: Circular economy models often require innovative technologies, processes, and services, leading to the emergence of new industries and job opportunities as shown in Figure 8 [118,119]. This contributes to economic growth and provides employment opportunities for individuals across different skill levels.
ii. *Community engagement*: Circular economy initiatives encourage collaboration and partnerships among various stakeholders, including local communities, businesses, and governments. This engagement fosters social cohesion, inclusivity, and active participation in decision-making processes.
iii. *Sustainable consumption*: Circular economy models promote a shift in consumer behavior towards sustainnable and responsible consumption practices. This includes raising awareness about the importance of resource conservation, supporting local and sustainable supply chains, and encouraging the use of eco-friendly products. These efforts contribute to a more sustainable society and empower consumers to make environmentally conscious choices.
iv. *Social equity and inclusion*: Circular economy models emphasize fair treatment of workers and aim to create products and systems that contribute to the well-being of communities. They prioritize social equity, ensuring that workers are provided with safe and fair working conditions throughout the supply chain [58].

Governance factors play a crucial role in facilitating the successful implementation of circular economy models in industrial chemistry and environmental engineering. They focus on transparent and accountable management, including the establishment of regulatory frameworks, stakeholder engagement, and reporting and disclosure mechanisms. Governments and regulatory bodies have the responsibility to develop supportive policies, regulations, and incentives that promote circular economy practices, such as extended producer responsibility programs and sustainable procurement practices [124-126].

The effective implementation of circular economy models heavily relies on the integration of robust Environmental, Social, and Governance (ESG) frameworks. Engaging stakeholders from diverse sectors, including government agencies, businesses, academia, and civil society, is essential to ensure their active participation and collaboration throughout the process. Transparency and accountability, crucial aspects of ESG, can be achieved through comprehensive reporting and disclosure of circular economy initiatives, performance, and impacts. This involves tracking and sharing ESG metrics and process updates. By embracing governance principles, organiza-tions can proficiently manage and implement circular economy models, thus contributing to the transition towards a more sustainable and circular system, with ESG and Cradle-to-Cradle (C2C) principles at the forefront. Driving the transition to a circular economy requires dedicated efforts such as sustainable material selection, resource efficiency, closing the loop, digitalization, and policy support. The integration of ESG factors ensures the consideration of environmental, social, and governance aspects in circular economy initiatives, fostering sustainability and positive societal impact. Collaborative endeavors, education and capacity building, circular supply chain management, and supportive policy and regulatory frameworks are vital for the successful implementation of circular economy practices. By embracing circularity and incorporating circular economy principles into industrial processes, the sectors of industrial chemistry and environmental engineering can make significant contributions to resource conservation, pollution reduction, and the overall well-being of the planet. This transition also holds the potential for economic growth and job creation.

It is imperative that government, businesses, academia, and civil society unite in collective action to create a more sustainable and resilient future. The integration of effective ESG and C2C frameworks, coupled with collaborative efforts and supportive policies, will pave the way towards a circular economy that promotes sustainability, resource efficiency, and well-being of both present and future generations.

9. Conclusion

The circular economy represents a transformative approach in the fields of industrial chemistry and environmental engineering, with a strong focus on resource efficiency, waste reduction, and sustainability. Key principles such as resource efficiency, waste valorization, recycling, sustainable product design, and industrial symbiosis are the driving forces behind the shift towards a more environmentally friendly industrial sector. Through the implementation of cleaner production methods, optimization of material flows, and enhanced collaboration between industries, the circular economy has the potential to significantly minimize environmental impacts and conserve natural resources. Crucially, green synthesis principles are vital to promote circularity within chemical processes by reducing the use of hazardous substances, minimizing waste generation, and improving resource efficiency. Mostly digital tools including data analytics, modeling, and monitoring systems play a pivotal role in facilitating informed decision-making, process optimization, and effective management of material flows, thereby supporting the transition towards a circular economy. The potential of the circular economy can be fully unlock, and collaboration and engagement among diverse stakeholders are paramount. Governments, regulatory bodies, industries, researchers, and consumers must work collectively to develop comprehensive circular economy strategies, implement sustainable practices, and address the challenges associated with transitioning towards circularity. Embracing circularity and adhering to the principles of the circular economy, the industrial chemistry and environmental engineering sectors can make substantial contributions to a more sustainable and prosperous future. This aligns with the United Nations Sustainable Development Goals (SDGs) and promotes responsible production and consumption patterns. The circular economy offers a promising approach to tackle global challenges and achieve sustainable development goals across a range of areas, including responsible consumption and production, clean energy, innovation and sustainable industrial practices, climate action, protection of ecosystems, water resource management, job creation and economic growth, sustainable urbanization, as well as collaboration and partnerships. By actively embracing the circular economy, these fields can drive positive change and contribute to the attainment of a more sustainable and prosperous future.

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