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REVIEW ARTICLE

Molecular Design Principles and Applications of Green Chemistry

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Abstract: Green chemistry is a fundamental shift in chemical sciences, emphasizing the design of chemical products and processes that minimize environmental impact while maintaining economic viability. The core principles of green chemistry guide the development of sustainable alternatives across multiple industrial sectors, from pharmaceuticals to materials science. Implementation of these principles has led to significant advancements in reaction methodologies, solvent selection, catalyst design, and waste reduction strategies. Recent developments in biocatalysis, continuous flow processing, and process intensification have demonstrated substantial improvements in both environmental and economic metrics. Industrial adoption of green chemistry approaches has resulted in reduced waste generation, improved energy efficiency, and enhanced worker safety. Applications span diverse sectors including pharmaceutical manufacturing, agrochemical development, materials processing, and water treatment technologies. Integration of green chemistry principles into academic curricula and industrial practice continues to drive innovation in sustainable chemical processing. The molecular-level approach to sustainability through green chemistry principles has proven effective in addressing environmental challenges while maintaining technological advancement and economic growth.

Keywords: Sustainable chemistry; Process optimization; Environmental impact; Biocatalysis; Clean technology

1. Introduction

The emergence of green chemistry at the beginning of the 1990s marked a transformative shift in chemical science and engineering, fundamentally altering the approach to chemical process design and implementation [1]. Green chemistry encompasses the design, development, and implementation of chemical products and processes that reduce or eliminate the use and generation of hazardous substances, while maintaining economic viability and technical performance [2]. The molecular-level approach to sustainability differentiates green chemistry from traditional environmental chemistry and remediation strategies. Rather than focusing on waste treatment and disposal, green chemistry emphasizes pollution prevention through innovative molecular design and process optimization [3]. This preventive approach has demonstrated significant advantages in terms of both environmental protection and economic efficiency [4].

Global adoption of green chemistry principles has led to the establishment of numerous governmental initiatives and research programs. The United States Presidential Green Chemistry Challenge Awards, established in 1995, pioneered the recognition of industrial and academic achievements in sustainable chemistry [5]. Subsequently, the formation of the Green Chemistry Institute in 1997 and the launch of dedicated scientific journals have created robust platforms for disseminating research advances and promoting industrial implementation [6]. The foundation of green chemistry rests upon twelve fundamental principles, articulated by Anastas and Warner, which serve as guidelines for chemical process design and optimization [7]. These principles address crucial aspects such as waste prevention, atom economy, energy efficiency, and the use of renewable feedstocks. The principles emphasize the importance of safer chemical syntheses, advocating for the use of benign substances and conditions throughout the chemical lifecycle [8].

Industrial implementation of green chemistry has demonstrated significant economic benefits through reduced waste treatment costs, improved energy efficiency, and enhanced process safety [9]. The pharmaceutical industry, in particular, has achieved notable success in implementing green chemistry principles, resulting in more efficient drug manufacturing processes with reduced environmental impact [10]. Contemporary challenges in chemical manufacturing, coupled with increasing environmental regulations and public awareness, have accelerated the adoption of green chemistry practices across various industrial sectors [11]. The integration of green chemistry principles with emerging technologies such as continuous flow processing, artificial intelligence, and advanced catalysis has opened new avenues for sustainable chemical production [12].

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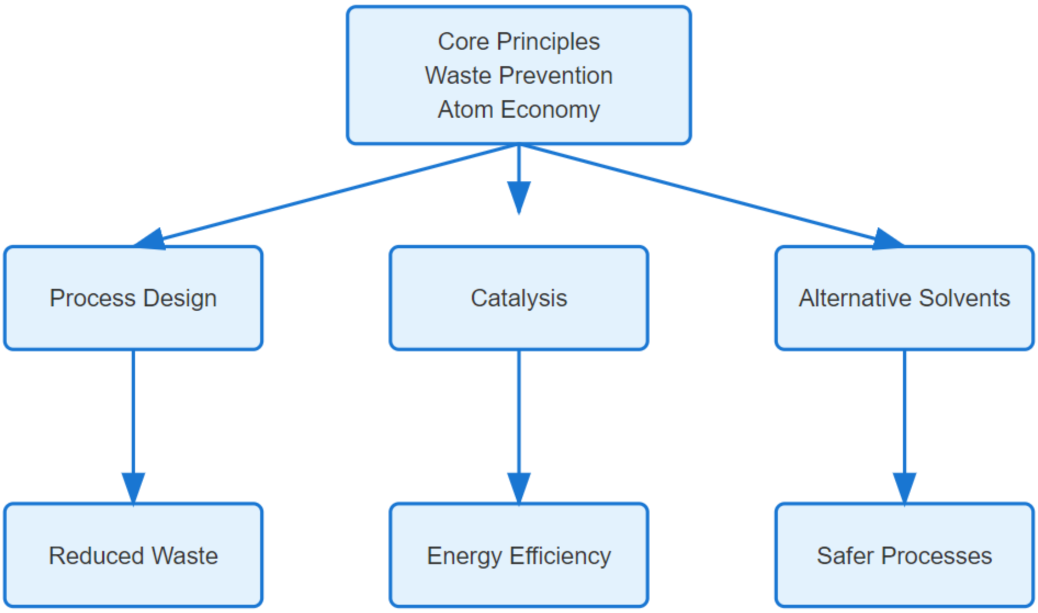

Figure 1. Implementation of Green Chemistry

Table 1. Comparison of Traditional vs. Green Chemistry Techniques in various Industrial Processes

Process Type	Traditional Approach	Green Chemistry Approach	Environmental Benefits
Solvent Use	Halogenated organic solvents	Water, supercritical CO_2, ionic liquids	Reduced toxicity, improved recyclability
Catalysis	Stoichiometric reagents	Catalytic processes	Lower waste generation, higher selectivity
Energy Input	High temperature/pressure	Ambient conditions, photocatalysis	Reduced energy consumption
Separation	Distillation, crystallization	Membrane separation, extraction	Lower energy requirements
Waste Treatment	End-of-pipe treatment	In-process prevention	Reduced environmental impact

2. Principles of Green Chemistry

The twelve principles of green chemistry establish a framework for developing sustainable chemical processes and products, addressing molecular design, reaction efficiency, and environmental impact [13]. These principles serve as guidelines for innovating safer and more efficient chemical transformations while maintaining economic viability [14].

2.1. Prevention and Waste Minimization

Prevention constitutes the primary principle, focusing on process design that inherently reduces waste generation. Modern synthetic strategies incorporate in-process monitoring and reaction optimization to minimize side product formation [15]. Real-time analytical techniques enable precise control of reaction parameters, significantly reducing batch failures and waste generation in industrial processes [16].

2.2. Atom Economy and Efficiency

Atom economy serves as a critical metric for evaluating synthetic route efficiency. Contemporary approaches prioritize addition reactions and cycloadditions over traditional substitution reactions that generate stoichiometric waste [17]. The development of multicomponent reactions has enabled the synthesis of complex molecules while maintaining high atom incorporation rates [18].

2.3. Hazard Reduction and Safety

Chemical process safety involves systematic evaluation of reaction conditions and reagent selection. Modern approaches utilize alternative reaction media such as supercritical fluids and bio-based solvents [19]. Process intensification strategies reduce hazardous material inventories while maintaining production efficiency [20].

2.4. Catalysis and Reaction Efficiency

Advanced catalytic systems enable reactions under milder conditions with improved selectivity. Recent developments in heterogeneous catalysis have produced recyclable catalysts maintaining activity over multiple cycles [21]. Biocatalytic approaches using engineered enzymes achieve highly selective transformations under environmentally benign conditions [22].

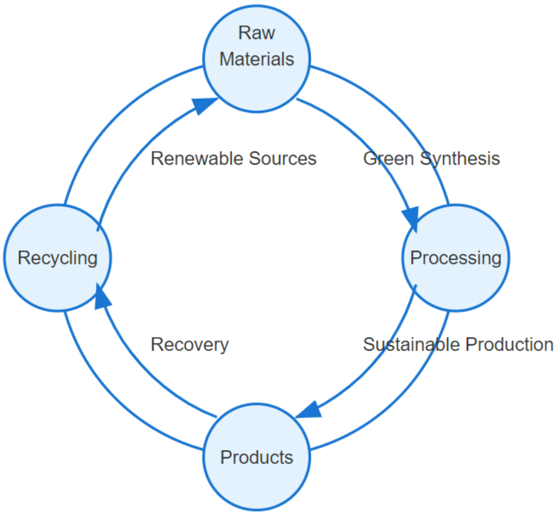

Figure 2. Process Flow in Green Chemistry

2.5. Energy Optimization

Energy optimization in chemical processes encompasses reaction engineering and process integration. Modern facilities implement heat exchange networks and energy recovery systems [23]. Alternative activation methods, including photocatalysis and electrochemical processes, enable ambient temperature reactions powered by renewable energy sources [24]

2.6. Renewable Resources and Feedstocks

Chemical manufacturing has witnessed a significant shift toward renewable feedstocks, particularly biomass-derived starting materials [25]. Lignocellulosic biomass conversion technologies provide sustainable routes to platform chemicals and functional materials [26]. Integration of biorefinery concepts with conventional chemical processing creates efficient pathways for sustainable production while reducing dependence on fossil resources [27].

3. Industrial Applications

3.1. Pharmaceutical Manufacturing

The pharmaceutical sector demonstrates successful implementation of green chemistry principles through innovative process designs and technological advances [28]. Continuous flow manufacturing enables precise reaction control while significantly reducing solvent consumption and improving safety profiles [29]. Enzymatic processes have revolutionized the synthesis of complex pharmaceutical intermediates, offering enhanced stereoselectivity and reduced environmental impact [30].

3.2. Agrochemical Production

Modern agrochemical synthesis incorporates green chemistry principles through:

- Enhanced catalytic processes that reduce toxic waste generation [31]
- Development of biodegradable pesticide formulations [32]
- Implementation of water-based extraction and purification methods [33]

3.3. Materials Science and Engineering

Materials processing has evolved to incorporate sustainable practices across multiple domains. Advanced polymer synthesis utilizes bio-based monomers and catalysts that operate under mild conditions [34]. Recycling technologies for polymeric materials have improved through the development of chemically recyclable polymers and efficient separation processes [35].

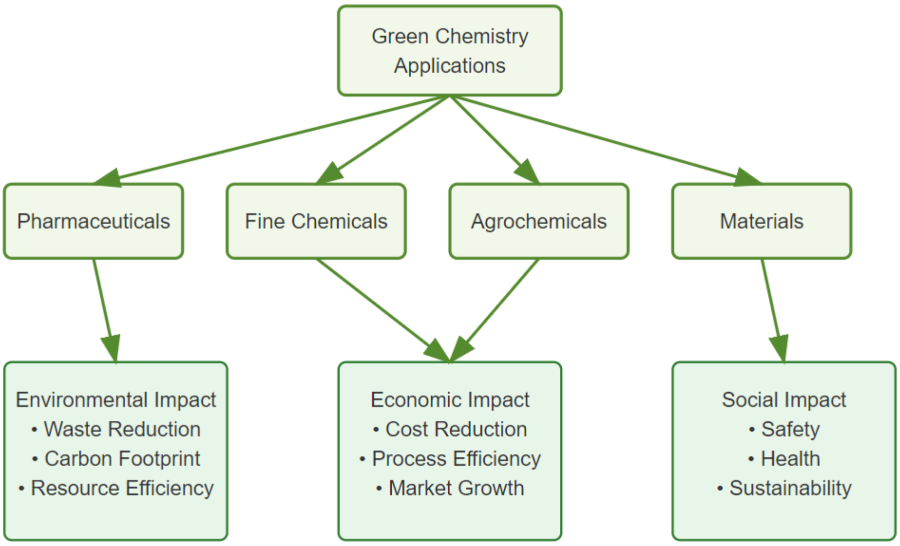

Figure 3. Industrial applications of Green Chemistry

3.4. Water Treatment

Green chemistry principles guide the development of sustainable water treatment solutions [36]. Advanced oxidation processes utilizing solar energy and catalytic systems provide efficient methods for contaminant degradation [37]. Novel adsorbent materials derived from renewable resources offer sustainable alternatives for water purification [38].

4. Process Integration and Optimization

4.1. Continuous Flow Processing

Continuous manufacturing systems represent a paradigm shift in chemical production [39]. These systems offer several advantages:

- Improved process control and safety
- Reduced energy consumption
- Enhanced reaction selectivity
- Minimized waste generation [40]

4.2. Process Intensification

Modern chemical manufacturing employs intensified processes that combine multiple unit operations [41]. Microreactor technology enables efficient mixing and heat transfer while reducing reaction volumes [42]. Membrane-based separation processes reduce energy requirements compared to traditional distillation methods [43].

4.3. Digital Process Control

Advanced process control systems integrate artificial intelligence and machine learning algorithms to optimize reaction conditions in real-time [44]. Digital twin technology enables precise simulation of chemical processes, facilitating optimization before physical implementation [45]. Predictive maintenance systems reduce unexpected shutdowns and associated waste generation, while automated control systems ensure consistent product quality [46].

5. Implementation

5.1. Assessment Tools

Evaluation methodologies measure the environmental impact of chemical processes through standardized metrics [47]. Life cycle assessment methodologies provide detailed analysis of environmental impacts across the entire product lifecycle [48]. Economic indicators integrate sustainability parameters with traditional cost analyses, enabling balanced decision-making in process development [49].

Table 2. Evaluation of Performance of Green Chemistry

Metric	Description	Formula/Calculation	Application
E-Factor	Measures total waste per kg of product	Total waste (kg)/Product (kg)	Process efficiency evaluation
Atom Economy	Efficiency of atom incorporation	(MW of product/MW of all reactants) × 100%	Reaction design
Process Mass Intensity (PMI)	Total mass used in process per mass of product	Total mass input/Mass of product	Manufacturing assessment
Carbon Efficiency	Carbon atoms in product vs. reactants	(C atoms in product/C atoms in reactants) × 100%	Carbon utilization
Reaction Mass Efficiency	Overall chemical yield considering stoichiometry	(Product mass × 100)/(Mass of all reactants)	Process optimization

5.2. Regulatory Guidelines

Environmental regulations increasingly emphasize preventive approaches aligned with green chemistry principles [50]. International standards and certification systems promote adoption of sustainable practices across industrial sectors [51]. Regulatory frameworks encourage innovation in sustainable chemistry through incentive programs and compliance requirements [52].

Table 3. Implementation Status of Green Chemistry Across Industries

Industry Sector	Most Implemented Principles	Implementation Level*	Challenges
Pharmaceuticals	Catalysis, continuous flow	High (75-90%)	Cost, regulatory compliance
Agrochemicals	Atom economy, biodegradability	Medium (50-75%)	Performance requirements
Polymers/Materials	Renewable feedstocks	Medium (50-75%)	Scale-up issues
Fine Chemicals	Waste prevention	High (75-90%)	Process complexity
Bulk Chemicals	Energy efficiency	Low (25-50%)	Infrastructure limitations

*Implementation level indicates estimated percentage of processes incorporating green chemistry principles

5.3. Education and Training

Academic institutions have integrated green chemistry principles into chemistry curricula at undergraduate and graduate levels [53]. Professional development programs provide industry practitioners with practical training in sustainable process design [54]. International collaborations facilitate knowledge transfer and best practice sharing across geographical boundaries [55].

6. Recent Trends

6.1. Novel Technologies

Artificial intelligence and machine learning applications accelerate the discovery of sustainable synthetic routes and catalyst systems [56]. Advanced materials design incorporates sustainability criteria from early development stages [57]. Quantum computing applications show promise in modeling complex chemical systems for optimized sustainable processes [58].

6.2. Circular Economy

Chemical manufacturing increasingly adopts circular economy principles through innovative recycling technologies [59]. Waste valorization strategies transform industrial byproducts into valuable chemical feedstocks [60]. Industrial symbiosis networks optimize resource utilization across multiple manufacturing facilities [61].

6.3. Sustainable Scale-up

Novel approaches to process scale-up maintain green chemistry principles during transition to industrial production [62]. Modular manufacturing systems enable flexible production while maintaining process efficiency [63]. Advanced simulation tools predict and optimize scale-up parameters, reducing material and energy waste during process development [64].

Table 4. Trends in Green Chemistry

Research Area	Current Status	Development Priority	Expected Timeline
AI/ML Integration	Emerging	High	2-3 years
Biocatalysis	Established	Medium	Ongoing
Flow Chemistry	Growing	High	1-2 years
Renewable Feedstocks	Developing	High	3-5 years
Circular Processing	Emerging	High	5-10 years

7. Challenges and Opportunities

7.1. Technical Challenges

Scale-up of sustainable processes often encounters challenges in maintaining efficiency and selectivity at industrial scales [65]. Complex separation requirements for bio-based feedstocks necessitate innovative purification technologies [66]. Integration of renewable energy sources into chemical manufacturing requires significant process modifications and infrastructure development [67].

7.2. Economic Factors

Initial capital investments for sustainable technologies often exceed conventional process costs, requiring careful economic justification [68]. Market volatility in renewable feedstock supplies impacts process economics and implementation decisions [69]. Development of new business models incorporates sustainability metrics into traditional economic evaluations, enabling more comprehensive cost-benefit analyses [70].

Table 5. Economic Impact of Green Chemistry Implementation

Parameter	Short-term Impact	Long-term Impact	ROI Timeline
Capital Investment	High (+20-30%)	Moderate (+10-15%)	3-5 years
Operating Costs	Moderate (+10-15%)	Low (-5-15%)	2-3 years
Waste Management	Low (-20-30%)	High (-40-50%)	1-2 years
Energy Costs	Moderate (-10-20%)	High (-30-40%)	2-4 years
Product Quality	Neutral (0%)	Positive (+10-20%)	3-5 years

7.3. Infrastructure Requirements

Transition to sustainable manufacturing requires substantial modifications to existing industrial infrastructure [71]. Development of integrated biorefinery complexes demands significant capital investment and long-term planning. Transportation and storage systems for renewable feedstocks and products need optimization and adaptation [72].

8. Conclusion

The evolution of green chemistry over the past three decades has transformed chemical manufacturing and process design approaches. The usage of sustainability principles for chemical processes has shown both environmental benefits and economic advantages across multiple industrial sectors. Significant advances in catalysis, process intensification, and renewable feedstock utilization have enabled more efficient and environmentally benign chemical production methods. The pharmaceutical and fine chemical industries have particularly benefited from green chemistry implementation, achieving substantial reductions in waste generation and energy consumption while maintaining product quality. Continuous flow processing, biocatalysis, and advanced separation technologies have emerged as key enablers of sustainable manufacturing practices. The usage of digital technologies and artificial intelligence continues to accelerate the discovery and optimization of sustainable chemical processes. Future success in green chemistry implementation will depend on continued innovation in catalysis and process design, along with supportive regulatory frameworks and economic incentives. Success in addressing current challenges while capitalizing on new opportunities will determine the pace and extent of green chemistry's continued evolution and impact on global chemical manufacturing.

References

[1] Anastas PT, Warner JC. Green chemistry: theory and practice. Oxford University Press; 1998.

[2] Clark JH. Green chemistry: today (and tomorrow). Green Chem. 2006;8(1):17-21.

[3] Sheldon RA. The E factor 25 years on: the rise of green chemistry and sustainability. Green Chem. 2017;19(1):18-43.

[4] Anastas P, Eghbali N. Green chemistry: principles and practice. Chem Soc Rev. 2010;39(1):301-12.

[5] Wilson MP, Schwarzman MR. Toward a new U.S. chemicals policy: rebuilding the foundation to advance new science, green chemistry, and environmental health. Environ Health Perspect. 2009;117(8):1202-9.

[6] Anastas PT, Kirchhoff MM. Origins, current status, and future challenges of green chemistry. Acc Chem Res. 2002;35(9):686-94.

[7] Anastas PT, Zimmerman JB. Design through the 12 principles of green engineering. Environ Sci Technol. 2003;37(5):94A-101A.

[8] Tang SLY, Smith RL, Poliakoff M. Principles of green chemistry: PRODUCTIVELY. Green Chem. 2005;7(11):761-2.

[9] Sheldon RA. Green and sustainable manufacture of chemicals from biomass: state of the art. Green Chem. 2014;16(3):950-63.

[10] Dunn PJ. The importance of green chemistry in process research and development. Chem Soc Rev. 2012;41(4):1452-61.

[11] Constable DJC, Curzons AD, Cunningham VL. Metrics to 'green' chemistry—which are the best? Green Chem. 2002;4(6):521-7.

[12] Tucker JL. Green chemistry, a pharmaceutical perspective. Org Process Res Dev. 2006;10(2):315-9.

[13] Jiménez-González C, Constable DJC, Ponder CS. Evaluating the "greenness" of chemical processes and products in the pharmaceutical industry—a green metrics primer. Chem Soc Rev. 2012;41(4):1485-98.

[14] Li CJ, Trost BM. Green chemistry for chemical synthesis. Proc Natl Acad Sci USA. 2008;105(36):13197-202.

[15] Sheldon RA, Woodley JM. Role of biocatalysis in sustainable chemistry. Chem Rev. 2018;118(2):801-38..

[16] Poliakoff M, Licence P. Sustainable technology: green chemistry. Nature. 2007;450(7171):810-2.

[17] Simon MO, Li CJ. Green chemistry oriented organic synthesis in water. Chem Soc Rev. 2012;41(4):1415-27.

[18] Jessop PG. Searching for green solvents. Green Chem. 2011;13(6):1391-8.

[19] Anastas PT, Kirchhoff MM, Williamson TC. Catalysis as a foundational pillar of green chemistry. Appl Catal A Gen. 2001;221(1-2):3-13.

[20] Clark JH, Farmer TJ, Hunt AJ, Sherwood J. Opportunities for bio-based solvents created as petrochemical and fuel products transition towards renewable resources. Int J Mol Sci. 2015;16(8):17101-59.

[21] Vaccaro L, Lanari D, Marrocchi A, Strappaveccia G. Flow approaches towards sustainability. Green Chem. 2014;16(8):3680-704.

[22] Bornscheuer UT, Huisman GW, Kazlauskas RJ, Lutz S, Moore JC, Robins K. Engineering the third wave of biocatalysis. Nature. 2012;485(7397):185-94.

[23] Gallezot P. Conversion of biomass to selected chemical products. Chem Soc Rev. 2012;41(4):1538-58.

[24] Lipshutz BH, Ghorai S. Transitioning organic synthesis from organic solvents to water. What's your E Factor? Green Chem. 2014;16(8):3660-79.

[25] Corma A, Iborra S, Velty A. Chemical routes for the transformation of biomass into chemicals. Chem Rev. 2007;107(6):2411-502.

[26] Ragauskas AJ, Williams CK, Davison BH, Britovsek G, Cairney J, Eckert CA, et al. The path forward for biofuels and biomaterials. Science. 2006;311(5760):484-9.

[27] Sheldon RA. Green solvents for sustainable organic synthesis: state of the art. Green Chem. 2005;7(5):267-78.

[28] Jiménez-González C, Poechlauer P, Broxterman QB, Yang BS, am Ende D, Baird J, et al. Key green engineering research areas for sustainable manufacturing: A perspective from pharmaceutical and fine chemicals manufacturers. Org Process Res Dev. 2011;15(4):900-11.

[29] Plutschack MB, Pieber B, Gilmore K, Seeberger PH. The Hitchhiker's guide to flow chemistry. Chem Rev. 2017;117(18):11796-893.

[30] Woodley JM. Accelerating the implementation of biocatalysis in industry. Appl Microbiol Biotechnol. 2019;103(12):4733-9.

[31] König B, Kümmel S, Svoboda E, Cibulka R. Photoredox catalysis in organic synthesis. Chem Rev. 2022;122(3):1493-523.

[32] Straathof AJJ, Panke S, Schmid A. The production of fine chemicals by biotransformations. Curr Opin Biotechnol. 2002;13(6):548-56.

[33] Huber GW, Iborra S, Corma A. Synthesis of transportation fuels from biomass: chemistry, catalysts, and engineering. Chem Rev. 2006;106(9):4044-98.

[34] Zhu Y, Romain C, Williams CK. Sustainable polymers from renewable resources. Nature. 2016;540(7633):354-62.

[35] Trost BM. The atom economy--a search for synthetic efficiency. Science. 1991;254(5037):1471-7.

[36] Sharma VK, Feng M. Water depollution using metal-organic frameworks-catalyzed advanced oxidation processes: A review. J Hazard Mater. 2019;372:3-16.

[37] Colmenares JC, Luque R. Heterogeneous photocatalytic nanomaterials: prospects and challenges in selective transformations of biomass-derived compounds. Chem Soc Rev. 2014;43(3):765-78.

[38] De Vos DE, Dams M, Sels BF, Jacobs PA. Ordered mesoporous and microporous molecular sieves functionalized with transition metal complexes as catalysts for selective organic transformations. Chem Rev. 2002;102(10):3615-40.

[39] Gutmann B, Cantillo D, Kappe CO. Continuous-flow technology—a tool for the safe manufacturing of active pharmaceutical ingredients. Angew Chem Int Ed. 2015;54(23):6688-728.

[40] Movsisyan M, Delbeke EIP, Berton JKET, Battilocchio C, Ley SV, Stevens CV. Taming hazardous chemistry by continuous flow technology. Chem Soc Rev. 2016;45(18):4892-928.

[41] Stankiewicz AI, Moulijn JA. Process intensification: transforming chemical engineering. Chem Eng Prog. 2000;96(1):22-34.

[42] Yoshida J, Takahashi Y, Nagaki A. Flash chemistry: flow chemistry that cannot be done in batch. Chem Commun. 2013;49(85):9896-904.

[43] Sholl DS, Lively RP. Seven chemical separations to change the world. Nature. 2016;532(7600):435-7.

[44] Coley CW, Green WH, Jensen KF. Machine learning in computer-aided synthesis planning. Acc Chem Res. 2018;51(5):1281-9.

[45] Krishnamurthy R. Giving rise to life: transition from prebiotic chemistry to protobiology. Acc Chem Res. 2017;50(3):455-9.

[46] Bourne RA, Rossen K. Machine Learning in Continuous Manufacturing and Process Analytical Technology. Trends Biotechnol. 2021;39(3):232-44.

[47] Jiménez-González C, Ponder CS, Broxterman QB, Manley JB. Using the right green yardstick: why process mass intensity is used in the pharmaceutical industry to drive more sustainable processes. Org Process Res Dev. 2011;15(4):912-7.

[48] Hellweg S, Milà i Canals L. Emerging approaches, challenges and opportunities in life cycle assessment. Science. 2014;344(6188):1109-13.

[49] Zimmerman JB, Anastas PT, Erythropel HC, Leitner W. Designing for a green chemistry future. Science. 2020;367(6476):397-400.

[50] Tickner JA, Becker M. Mainstreaming green chemistry: The need for metrics. Curr Opin Green Sustain Chem. 2016;1:1-4.

[51] Clark JH, Summerton L, Hunt AJ. Green chemistry for the circular economy. Green Chem. 2019;21(18):4839-44.

[52] Anastas PT, Zimmerman JB. The United Nations sustainability goals: How can sustainable chemistry contribute? Curr Opin Green Sustain Chem. 2018;13:150-3.

[53] Andraos J, Dicks AP. Green chemistry teaching in higher education: a review of effective practices. Chem Educ Res Pract. 2012;13(2):69-79.

[54] Mattes JJ, Steffensen G, Francl M. Integrating green chemistry throughout the undergraduate curriculum via civic engagement. J Chem Educ. 2020;97(8):2185-91.

[55] Horváth IT, Anastas PT. Innovations and green chemistry. Chem Rev. 2007;107(6):2169-73.

[56] Gromski PS, Henson AB, Granda JM, Cronin L. How to explore chemical space using algorithms and automation. Nat Rev Chem. 2019;3(2):119-28.

[57] Matlin SA, Mehta G, Hopf H, Krief A. The role of chemistry in inventing a sustainable future. Nat Chem. 2015;7(12):941-3.

[58] Aspuru-Guzik A, Lindh R, Reiher M. The matter simulation (r)evolution. ACS Cent Sci. 2018;4(2):144-52.

[59] Ellen MacArthur Foundation. The new plastics economy: rethinking the future of plastics & catalysing action. Ellen MacArthur Foundation. 2017.

[60] Tuck CO, Pérez E, Horváth IT, Sheldon RA, Poliakoff M. Valorization of biomass: deriving more value from waste. Science. 2012;337(6095):695-9.

[61] Chertow MR, Park J. Scholarship and practice in industrial symbiosis: 1989–2014. In: Taking Stock of Industrial Ecology. Springer; 2016:87-116.

[62] Jiménez-González C, Constable DJC. Green Chemistry and Engineering: A Practical Design Approach. John Wiley & Sons; 2011.

[63] Buchholz S. Future manufacturing approaches in the chemical and pharmaceutical industry. Chem Eng Process. 2010;49(10):993-5.

[64] Rogers L, Jensen KF. Continuous manufacturing - the Green Chemistry promise? Green Chem. 2019;21(13):3481-98.

[65] Sheldon RA. Metrics of green chemistry and sustainability: past, present, and future. ACS Sustain Chem Eng. 2018;6(1):32-48.

[66] Werpy T, Petersen G. Top value added chemicals from biomass: Volume I - Results of screening for potential candidates from sugars and synthesis gas. National Renewable Energy Lab; 2004.

[67] Lanzafame P, Centi G, Perathoner S. Evolving scenarios for biorefineries and the impact on catalysis. Catal Today. 2014;234:2-12.

[68] Nikolau BJ, Perera MADN, Brachova L, Shanks B. Platform biochemicals for a biorenewable chemical industry. Plant J. 2008;54(4):536-45.

[69] Clark JH. Green chemistry: challenges and opportunities. Green Chem. 1999;1(1):1-8.

[70] Anastas PT, Beach ES. Green chemistry: the emergence of a transformative framework. Green Chem Lett Rev. 2007;1(1):9-24.

[71] Gallezot P. Process options for converting renewable feedstocks to bioproducts. Green Chem. 2007;9(4):295-302.

[72] FitzPatrick M, Champagne P, Cunningham MF, Whitney RA. A biorefinery processing perspective: treatment of lignocellulosic materials for the production of value-added products. Bioresour Technol. 2010;101(23):8915-22.