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The Need of Chemical Sustainability in Advancing Sustainable Chemistry

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ABSTRACT

Chemical sustainability is pivotal in the advancement of sustainable chemistry, playing a critical role in addressing global environmental challenges. This abstract explores the principles and practices of chemical sustainability, emphasizing its contribution to sustainable chemistry through the development of eco-friendly processes and products. Sustainable chemistry seeks to minimize the environmental impact of chemical manufacturing and usage by promoting the use of renewable resources, reducing waste, and enhancing energy efficiency. Key strategies include the design of greener synthesis pathways that utilize less hazardous substances, the adoption of catalytic processes that increase reaction efficiency, and the implementation of circular economy principles that encourage the reuse and recycling of materials. Innovations in green chemistry, such as the development of biodegradable polymers and sustainable solvents, exemplify the potential for chemical sustainability to create more environmentally benign alternatives to traditional chemicals. Interdisciplinary collaboration and the integration of life cycle assessment tools are essential for evaluating the sustainability of chemical processes and products. This holistic approach ensures that the environmental, economic, and social dimensions of sustainability are considered. Chemical sustainability is a cornerstone of sustainable chemistry, driving the transition toward more sustainable industrial practices and fostering a healthier environment. By prioritizing sustainability, the chemical industry can significantly contribute to global efforts in achieving a more sustainable and resilient future.

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INTRODUCTION

Chemical sustainability has emerged as a crucial area within the broader field of sustainable chemistry, driving innovation to address environmental challenges and promote sustainable development. Enhancing sustainability across the entire life cycle of chemicals, from raw material extraction to end-of-life management, has become a priority for manufacturers, policymakers, and consumers alike. This approach encompasses diverse aspects, including the valorization of renewable feedstocks like cellulose and biomass, the development of green chemistry principles, the implementation of additive manufacturing processes, and the pursuit of a circular economy.[1]

By embracing chemical sustainability, stakeholders aim to optimize resource utilization, minimize environmental impacts, and foster economic growth while safeguarding human health and ecological systems. This multifaceted endeavor requires a holistic understanding of chemical processes, toxicology, and environmental science, enabling the design of safer products, the adoption of biochar and sustainable solvents, and the recovery and reuse of innovative materials like ionic liquids [2-5] (Fig. 1).

A. Sustainable Solvents for Alginate Extraction

Alginate is an inexpensive polymer that is extracted from brown algae or synthesized by the microorganisms Azotobacter and Pseudomonas. Its low cost and unique solubility make alginate a promising membrane polymer for organic solvent nanofiltration (OSN).

B. Ionic Liquids and Deep Eutectic Solvents

Ionic liquids (ILs) are salts composed of a large organic cation and a smaller organic or inorganic anion, with a

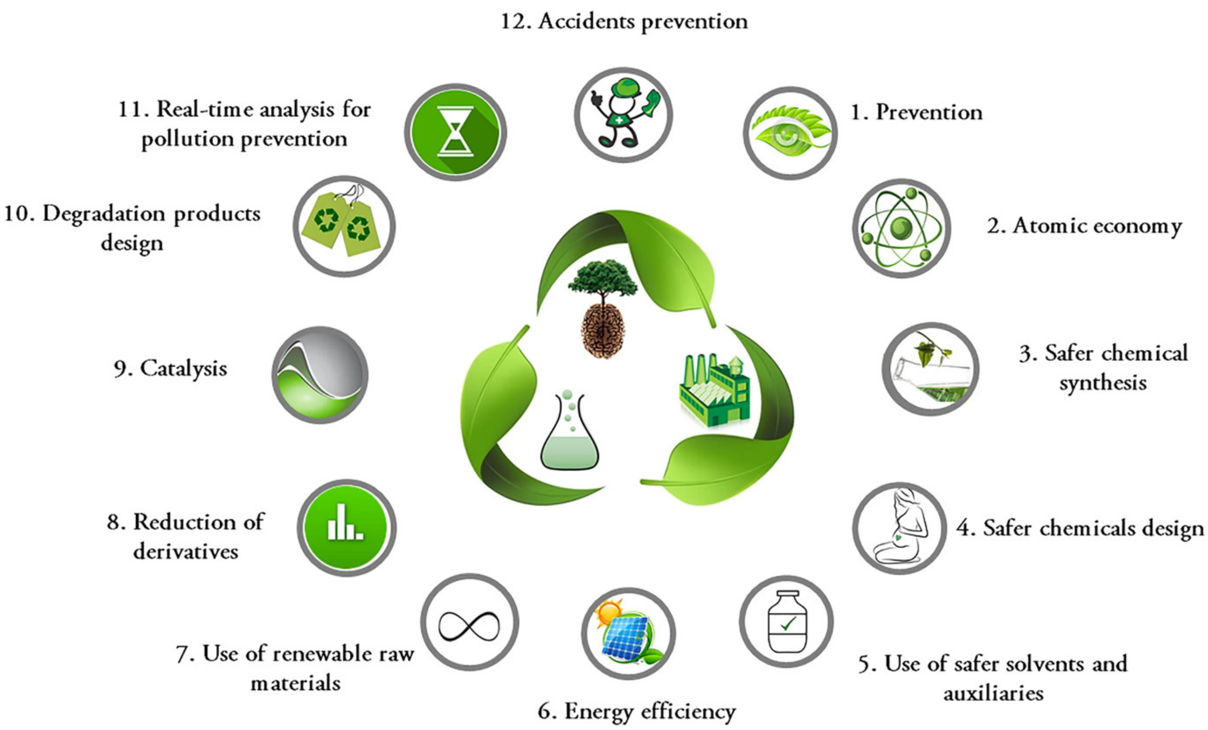


Fig. 1: Sustainable Manufacturing in the Chemicals Industry

melting temperature below 100°C. Their low melting point is governed by their low charge density and low symmetry ions. ILs are considered “designer solvents” due to the numerous combinations of cations and anions that can form an IL, allowing them to be tailored for specific applications. ILs generally have interesting properties such as electrical conductivity, negligible vapor pressure, low flammability, tunability, and excellent thermal stability, making them good solvents for a wide range of polar and non-polar compounds.[6]

Deep eutectic solvents (DESs) are mixtures of solid compounds that form a eutectic mixture with a lower melting point than each individual component. This melting point depression is attributed to the hydrogen bonding network established among components and the charge delocalization resulting from it. DESs are composed of at least one hydrogen bond donor (HBD) and one hydrogen bond acceptor (HBA). They are cheap to produce, possess low toxicity (especially those derived from renewable resources), and have applications in biomass fractionation and extraction.[7-9]

C. Aqueous Solutions of Ionic Liquids

Experiment 1 involved a beaker containing 10 g of individual ILs (each IL tested separately) and 500 mg of seaweed powder. In Experiment 2, 500 mg of seaweed powder was mixed with ILs containing 10% water. Similarly, in Experiment 3, 500 mg of seaweed powder was combined with 10 g of individual DESs, and Experiment 4 involved 500 mg of seaweed powder with DESs containing 10% water.

All IL ions (cation and anions) display hydrogen bondability with alginate’s structure. However, IL cations ([Ch]+) also show electrostatic interaction from a nitrogen atom (positively charged) to an alginate carbonyl group (COOH). The hydrogen bondability of the tested ILs increased in the order of [Ch][Acetate] < [Ch][Formate] < [Ch][Glycolate], and the experimental results obtained show a similar trend of extraction yields, indicating that hydrogen bondability is a major driving force for alginate extraction (higher hydrogen bondability to alginate structure leads to higher extraction yields).[10-13]

D. Molecular Docking Studies

All IL anions interact only with alginate hydroxyl groups, allowing IL cations to interact with alginate carbonyl groups. On the other hand, the IL counterpart DESs with acetic, formic, and glycolic acids were not able to extract alginate. The docking affinity of DES HBDs decreases in the order of glycolic acid < acetic acid < formic acid. All HBDs exhibit higher hydrogen bondability compared to their IL analog anions, so they were expected to be more effective in alginate extraction. However, the stability of DESs in aqueous solutions at lower concentrations was the main reason for the absence of results at an experimental level. The amount of water could promote a decrease in interactions between the DESs of HBA and HBD, causing both components to act as individual compounds in water solution and not as a solvent, making it difficult to predict the impact of DESs on the extraction procedure [14]-[15].

Characterization and Rheological Properties of Extract ed Alginate

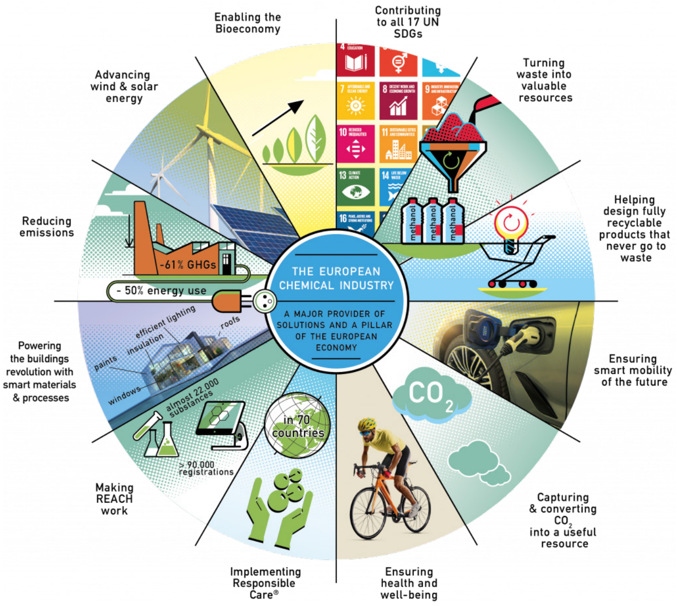


Fig. 2: Characterization and Rheological Properties

The impact on the M/G ratio is also negligible. It was concluded that the sodium alginate route not only had the simplest steps, but also resulted in the highest yield with good overall rheological properties. The calcium route led to a product with the lowest molecular weight and poor mechanical properties. It is explained that the degradation of the ether bond by HCl (which is used in both the calcium alginate and alginic acid routes) was responsible for the low molecular weight and weak mechanical properties (Fig. 2).

A. Comparison with Conventional Extraction Methods

In another study comparing the calcium and alginic acid routes using the brown seaweed Sargassum sp, the calcium route led to a higher yield and a better product than that of the alginic acid route. However, the comparison of these two routes with the sodium alginate route was not reported and the product was the alginic acid form instead of sodium alginate.

B. Yield and Quality of Alginate

The best extraction yield observed was 45.54%, while molecular weight up to 217.94 kDa could be achieved. Interestingly, the M/G ratio of the alginate product was only 0.29, indicating a very high guluronate content in the polysaccharide. As the parallel conventional extraction method was not carried out, it is not known whether low M/G ratio is due to the seaweed species or related to the specific ExAE method [16]-[17].

Recovery and Reuse of Ionic Liquids

Another significant environmental benefit of ionic liquids is their recyclability. Their non-volatile nature simplifies the separation of desired products from the reaction mixtures and the recovery of the ionic liquid itself. This aspect not only minimizes waste generation but also reduces the demand for producing new solvents. The ability to reuse these materials multiple times without significant degradation in performance underscores their role in promoting sustainable industrial practices and reducing the overall ecological footprint of chemical manufacturing.

A. Distillation

Distillation is the most commonly used process for separating liquid mixtures through gradient boiling and condensation based on the differences in the volatility of the components in the mixture. Due to simple operation, distillation has been widely applied for the recovery of ionic liquids (ILs). During the process, according to the types of the distillates, the distillation could be operated in three ways:

1. Distillation of volatile species while leaving the ionic liquids in the distillation equipment.
2. Distillation through the reaction of ILs, where ILs form distillable carbene or decompose into distillable neutral compounds.
3. Distillation of ILs as intact ion pairs.

B. Liquid-Liquid Extraction

Liquid-liquid extraction is a separation method based on the difference in solubility of the separated components in two immiscible liquid phases. It has been proved to be an efficient method for recovering ILs. Different solvents such as water, organic solvents, and supercritical carbon dioxide (scCO2) have been employed during the extraction processes.[12-19]

C. Adsorption

Adsorption has been utilized as a robust and non-destructive method to promote recovery or removal of ILs. Up to date, a variety of adsorbents, such as activated carbons, soils and sediments, ion exchange resins, and biosorbents, etc., have been investigated. With low melting point, extremely low vapor pressure, and nonflammability, ionic liquids have been attracting much attention from academic and industrial fields. Great efforts have been made to facilitate their applications in catalytic processes, extraction, desulfurization, gas separation, hydrogenation, electronic manufacturing, etc. To reduce the cost and environmental effects, different technologies have been proposed to recover the ionic liquids from different solutions after their application.

During the past decades, great attempts have been made by researchers for the recovery and recycling of ILs, including distillation, extraction, adsorption, membrane separation, aqueous two-phase extraction, crystallization, and force field separation, etc., as shown in Fig. 1. Among these methods, distillation and extraction are two of the most commonly used ways.[20-23]

VALORIZATION OF RESIDUAL BIOMASS

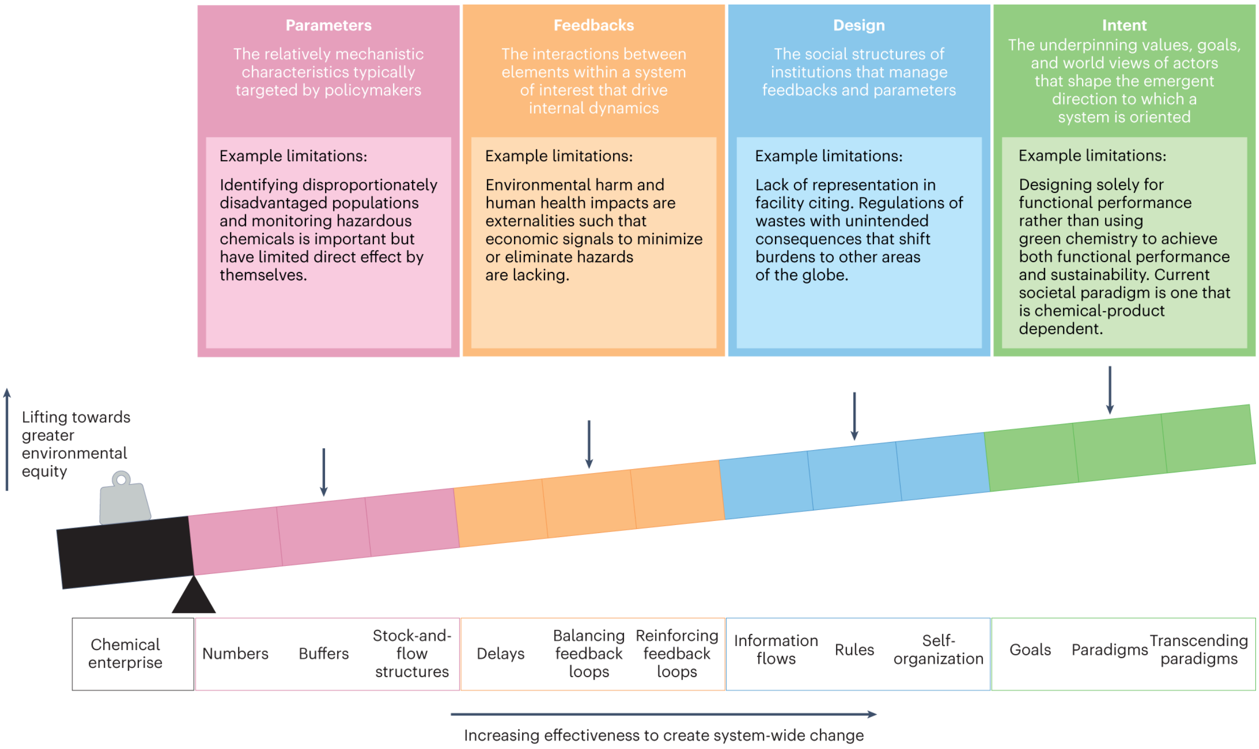
Lignocellulosic biomass is a very desirable feedstock for biofuel production. If the fermentation process for lignocellulose could be optimized, conversion of this biomass could yield 25 to 50 billion gallons of ethanol per year. However, lignocellulose, which is composed of lignin, cellulose and hemicellulose, is resistant to chemical or enzymatic hydrolysis. This resistance is a key limiting step in the conversion of biomass into fermentable sugars.[24-25]

A. Conversion to Cellulose

UW-Madison researchers have developed a new method for degrading lignocellulosic biomass to fermentable sugars. This simple, high-yielding chemical process, which involves the gradual addition of water to a chloride ionic liquid, enables crude biomass to serve as the sole source of carbon for a scalable biorefinery. In this method, biomass is mixed with a cellulose-dissolving ionic liquid and heated to form a solution or gel. Then water and an acid catalyst are added, and the resulting mixture is heated, typically to 105°C. At specified time intervals, more water is added to the mixture until it contains more than 20 percent water by weight. At this point, the mixture contains free sugars such as xylose and glucose and unhydrolyzed carbohydrate polymers, which often are not dissolved. The insoluble materials, acid, and ionic liquids are separated from the soluble sugars. The soluble sugars then can serve as the sole carbon source for microorganisms such as E. coli KO11, an ethanologen.[26-29]

Key Benefits:

1. Provides a simple chemical process that enables crude biomass to be the sole source of carbon for a scalable biorefinery.
2. High conversion of biomass - yields of glucose or xylose typically are 70 to 80 percent.



Parameters

The relatively mechanistic characteristics typically targeted by policymakers

Example limitations:

Identifying disproportionately disadvantaged populations and monitoring hazardous chemicals is important but have limited direct effect by themselves.

Feedbacks

The interactions between elements within a system of interest that drive internal dynamics

Example limitations:

Environmental harm and human health impacts are externalities such that economic signals to minimize or eliminate hazards are lacking.

Design

The social structures of institutions that manage feedbacks and parameters

Example limitations:

Lack of representation in facility citing. Regulations of wastes with unintended consequences that shift burdens to other areas of the globe.

Intent

The underpinning values, goals, and world views of actors that shape the emergent direction to which a system is oriented

Example limitations:

Designing solely for functional performance rather than using green chemistry to achieve both functional performance and sustainability. Current societal paradigm is one that is chemical-product dependent.

Fig. 3: Green chemistry path

3. Provides high sugar yields within hours at 105°C.
4. Low byproduct formation.
5. Effective with both cellulose and corn stover.
6. Comparable to enzymatic hydrolysis.
7. Does not require concentrated strong acid, expensive enzymes or chemical pretreatment as a separate step.
8. Ionic liquid can be recovered.
9. Lignin residue is relatively unmodified, making it an excellent feedstock for high-value lignin products.

5. Sustainability and Environmental Impact

A. Reduced Carbon Footprint

The chemical industry plays a critical role in the global economy, providing essential raw materials for various products and industries. However, chemical manufacturing is a highly energy-intensive process that often results in significant carbon emissions. These emissions contribute to climate change, global warming, melting of ice caps, rising sea levels, and increased frequency of extreme weather events. Reducing the carbon footprint of the chemical industry is crucial for mitigating the adverse effects of climate change and protecting the environment for current and future generations. One primary way to reduce carbon emissions in chemical manufacturing is to shift to renewable energy sources such as solar, wind, and hydropower. These sources can power manufacturing processes, reducing the reliance on fossil fuels and lowering carbon emissions. Additionally, chemical manufacturers can install on-site renewable energy systems to further reduce their reliance on the grid and carbon footprin[30] (Fig. 3).

Implementing energy efficiency measures is another effective approach to reducing carbon emissions. Process optimization, waste heat recovery, and upgrading to more energy-efficient equipment can significantly reduce the amount of energy required for manufacturing chemicals. These measures not only reduce carbon emissions but can also result in cost savings for the manufacturers. Incorporating sustainable materials in manufacturing processes can also contribute to a lower carbon footprint. The use of biodegradable, non-toxic materials, and the incorporation of recycled materials can reduce the need for new raw materials and minimize waste generation, thereby reducing carbon emissions. Adopting circular economy models focused on reducing waste and maximizing resource utilization can help chemical manufacturers reduce their carbon footprint while realizing economic benefits. These models involve the reuse of materials and products, the recycling of waste, and the recovery of energy from waste.[31]

B. Waste Minimization

Waste minimization refers to strategies aimed at preventing waste through upstream interventions, emphasizing the importance of avoiding waste creation rather than managing residuals after generation.

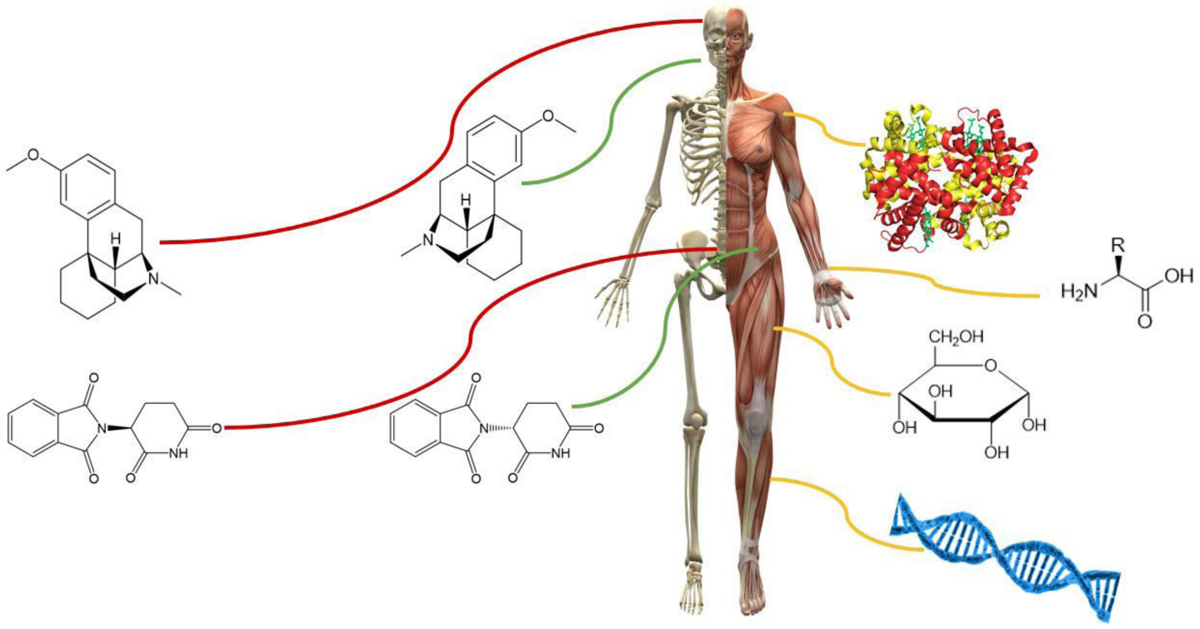


Fig. 4: Education - Green Chemistry

Strategies such as product design, cleaner production, reuse of scrap material, improved quality control, and waste exchanges can minimize waste and improve resource efficiency in or even before the manufacturing process. Waste minimization activities achieved through the application of green chemistry principles are at the root of the solution, especially for chemical waste minimization. Green chemistry promotes waste minimization and plays a significant role in achieving industrial ecology goals. Despite its enormous potential, the green chemistry approach is still underestimated (Fig. 5).

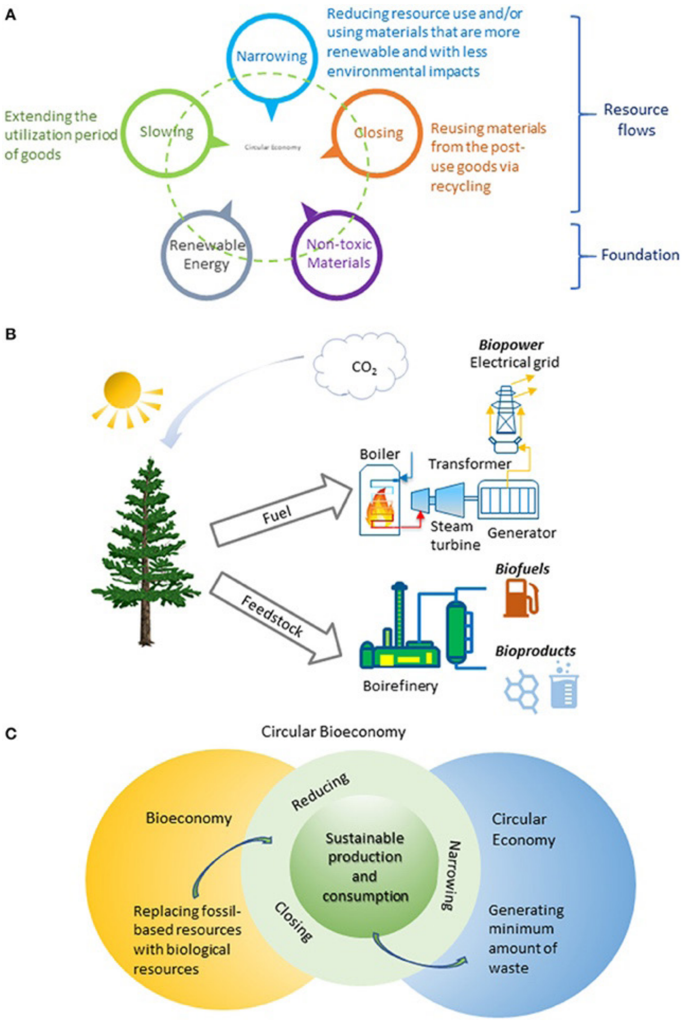


Fig. 5: Circular Bioeconomy Concepts

Waste prevention involves reducing the quantity and quality of waste at the source, reducing the use of raw materials and energy, and promoting reuse. Mapping resource use and waste generation, as well as sharing the knowledge of waste minimization concepts with the chemical industry, are crucial challenges to be addressed. Research in green chemistry can contribute to establishing a culture of waste minimization in industries like chemicals, pharmaceuticals, and bulk drugs. In laboratories, waste minimization can be achieved through various practices. Substituting hazardous chemicals with non-hazardous alternatives, modifying procedures or processes, implementing good laboratory practices such as computer modeling and small-scale experiments, and maintaining proper inventory control and housekeeping can effectively minimize waste generation. Additionally, keeping hazardous waste separate from non-hazardous waste and providing training to personnel can further reduce waste. Waste prevention and minimization have positive environmental, human health and safety, and economic impacts. Implementing a “less is better” concept provides better protection of human health and safety by reducing exposures, generates less demand for disposal on the environment, and lowers disposal costs.

FUTURE PERSPECTIVES

The world is increasingly recognizing the need for sustainable practices across all industries, including chemical manufacturing. To address these concerns, the industry is undergoing a significant transformation, embracing sustainable practices and developing innovative solutions.

A. Green Chemistry and Sustainable Processes

Green chemistry, also known as sustainable chemistry, aims to design chemical processes that minimize the use and generation of hazardous substances. Through the application of green chemistry principles, chemical manufacturers are developing cleaner and safer production methods, reducing the environmental footprint of their operations (Fig. 6).

B. Renewable Feedstocks and Bio-based Chemicals

One of the key trends in sustainable chemical manufacturing is the shift towards renewable feedstocks and bio-based chemicals. Bio-based chemicals not only reduce dependence on fossil fuels but also offer the potential for lower carbon emissions and improved biodegradability compared to their petrochemical counterparts.

C. Circular Economy and Resource Efficiency

The concept of a circular economy is gaining traction in the chemical industry. Rather than following a linear “take-make-dispose” model, the circular economy aims to close the loop by promoting resource efficiency, recycling, and the recovery of valuable materials. Chemical manufacturers are adopting strategies to

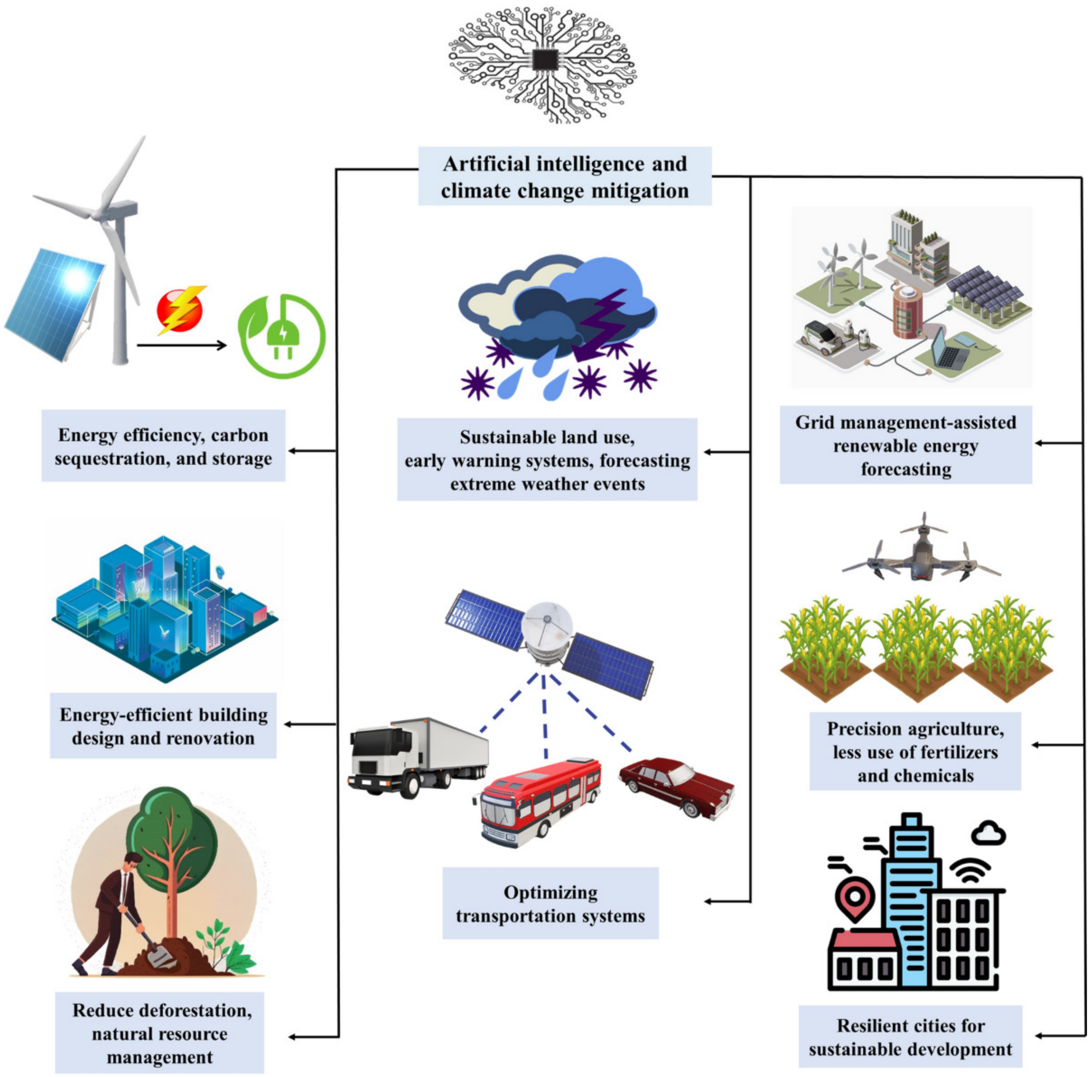


Fig. 6: Artificial intelligence-based solutions for climate change

minimize waste generation, increase recycling rates, and develop innovative processes for the recovery and reuse of chemicals.

D. Energy Management and Carbon Neutrality

Energy management and carbon neutrality have become crucial goals for sustainable chemical manufacturing. Companies are increasingly investing in energy-efficient technologies, such as process optimization, heat integration, and cogeneration, to reduce energy consumption and greenhouse gas emissions. Furthermore, the adoption of renewable energy sources, including solar and wind power, is gaining momentum in the industry.

E. Digitalization and Data Analytics

Digitalization and data analytics are revolutionizing the chemical manufacturing landscape. Advanced data collection and analysis tools enable real-time monitoring, process optimization, predictive maintenance, and resource allocation. By leveraging big data, artificial intelligence, and machine learning algorithms, chemical manufacturers can enhance process efficiency, reduce waste, and make informed decisions that drive sustainability improvements.

F. Noah Chemicals’ Commitment to Sustainability

Noah Chemicals is at the forefront of sustainable chemical manufacturing, embracing emerging trends that prioritize environmental stewardship and long-term sustainability. By implementing green chemistry principles, utilizing renewable feedstocks, embracing circular economy strategies, prioritizing energy management, and leveraging digitalization, Noah Chemicals is leading the way in minimizing the environmental impact of chemical production.

CONCLUSIONS

The transition towards chemical sustainability represents a pivotal shift in the chemical industry, fostering innovative solutions that harmonize economic growth with environmental stewardship. By embracing principles such as green chemistry, valorization of renewable feedstocks, and the recovery and reuse of innovative materials, stakeholders can optimize resource utilization while minimizing environmental impacts. This multifaceted approach not only enhances sustainability across the entire life cycle of chemicals but also unlocks new avenues for sustainable development. Ultimately, the pursuit of chemical sustainability extends beyond technological advancements, encompassing a fundamental shift in mindset and operational paradigms. As we continue to explore and implement sustainable practices, we pave the way for a future where the chemical industry contributes to a thriving economy while safeguarding the planet for generations to come. By fostering collaboration, innovation, and a shared commitment to sustainability, the chemical sector can play a pivotal role in building a more sustainable and resilient world.

REFERENCES:

1. DeSimone, J. M. (2002). Practical approaches to green solvents. Science, 297 (5582), 799-803.
2. Anastas, P. T., & Eghbali, N. (2010). Green chemistry: Principles and practice. Chemical Society Reviews, 39 (1), 301-312.
3. Erythropel, H. C., Zimmerman, J. B., de Winter, T. M., Petitjean, L., Melnikov, F., Lam, C. H., & Anastas, P. T. (2018). The Green ChemisTREE: 20 years after taking root with the 12 principles. Green Chemistry, 20 (9), 1929-1961.
4. Clark, J. H., & Deswarte, F. E. I. (2015). Introduction to Chemicals from Biomass. Wiley.
5. Collins, T. J. (2012). Towards sustainable chemistry. Science, 291 (5501), 48-49.
6. Garcia, E. E., López-Sabirón, A. M., Ferreira, G., & Stuber, M. D. (2019). Life cycle assessment of green chemical processes. Current Opinion in Green and Sustainable Chemistry, 19 , 40-45.
7. Tundo, P., Anastas, P. T., Black, D. S., Breen, J., Collins, T., Memoli, S., & Poliakoff, M. (2000). Synthetic pathways and processes in green chemistry. Introductory overview. Pure and Applied Chemistry, 72 (7), 1207-1228.
8. Selvam, L., et al. “Collaborative autonomous system based wireless security in signal processing using deep learning techniques.” Optik 272 (2023): 170313.
9. Gathergood, N., & Scammells, P. J. (2002). Biodegradable ionic liquids: Part I. Concept, preliminary targets, and evaluation. Green Chemistry, 4 (5), 479-482.
10. Warner, J. C. (2019). Beyond benign: Green chemistry education. ACS Sustainable Chemistry & Engineering, 7 (9), 7559-7561.
11. Babu, D. Vijendra, et al. “Digital code modulation-based MIMO system for underwater localization and navigation using MAP algorithm.” Soft Computing (2023): 1-9.
12. Gross, R. A., & Kalra, B. (2002). Biodegradable polymers for the environment. Science, 297 (5582), 803-807.
13. Shonnard, D. R., Kicherer, A., & Saling, P. (2003). Industrial applications using BASF eco-efficiency analysis: Perspectives on green engineering principles. Environmental Science & Technology, 37 (23), 5340-5348.
14. Rani, B. M. S., et al. “Disease prediction based retinal segmentation using bi-directional ConvLSTMU-Net.” Journal of Ambient Intelligence and Humanized Computing (2021): 1-10.
15. Hatti-Kaul, R., Törnvall, U., Gustafsson, L., & Börjesson, P. (2007). Industrial biotechnology for the production of bio-based chemicals–a cradle-to-grave perspective. Trends in Biotechnology, 25 (3), 119-124.
16. Wilson, M. P., & Schwarzman, M. R. (2009). Toward a new U.S. chemicals policy: Rebuilding the foundation to advance new science, green chemistry, and environmental health. Environmental Health Perspectives, 117 (8), 1202-1209.
17. Nizam, Taaha, et al. “Novel all-pass section for high-performance signal processing using CMOS DCCII.” TENCON 2021-2021 IEEE Region 10 Conference (TENCON). IEEE, 2021.
18. Horváth, I. T., & Cséfalvay, E. (2021). Sustainability assessment in chemical processes. Current Opinion in Green and Sustainable Chemistry, 32 , 100535.
19. Jessop, P. G., & Leitner, W. (1999). Supercritical Carbon Dioxide as a Green Solvent: Sustainable Technologies. Wiley-VCH.
20. Kerton, F. M., & Marriott, R. (2013). Alternative Solvents for Green Chemistry. Royal Society of Chemistry.
21. Linthorst, J. A. (2010). An overview: origins and development of green chemistry. Foundations of Chemistry, 12 (1), 55-68.
22. Zhang, W., Cue, B. W., & Mo, T. (2018). Green chemistry in pharmaceutical manufacturing: challenges and opportunities. Organic Process Research & Development, 22 (7), 840-851.
23. Vijay, V. and Srinivasulu, A., “A novel square wave generator using second-generation differential current conveyor,” Arabian Journal for Science and Engineering, 42(12), 2017, pp.4983-4990.
24. Matlack, A. S. (2010). Introduction to Green Chemistry. CRC Press.
25. McDonough, W., & Braungart, M. (2002). Cradle to Cradle: Remaking the Way We Make Things. North Point Press.

26. Moser, B. R. (2011). Biodiesel production, properties, and feedstocks. In Vitro Cellular & Developmental Biology-Plant, 47 (2), 208-214.
27. Poliakoff, M., Fitzpatrick, J. M., Farren, T. R., & Anastas, P. T. (2002). Green chemistry: Science and politics of change. Science, 297 (5582), 807-810.
28. Zimmerman, J. B., Anastas, P. T., Erythropel, H. C., & Leitner, W. (2020). Designing for a green chemistry future. Science, 367 (6485), 397-400.
29. Pittala, C.S., et al., “1-Bit FinFET carry cells for low voltage high-speed digital signal processing applications,” Silicon, 15(2), 2023, pp.713-724.
30. Rani, B.M.S., et al., “Road Identification Through Efficient Edge Segmentation Based on Morphological Operations,” Traitement du Signal, 38(5), 2021.
31. Sheldon, R. A. (2016). Green and sustainable manufacture of chemicals from biomass: state of the art. Green Chemistry, 18 (12), 3180-3183