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Advancing Sustainable and Green Chemistry: Principles, Innovations, and Implementation

Vinod Kumar Singh
Associate professor, Department of chemistry, K.G.K. (PG) college Moradabad.
Mail- vinod.ap81@yahoo.in

Abstract:

Sustainable development is a key challenge of the twenty-first century, exacerbated by resource consumption, pollution, ecosystem degradation, and biodiversity loss among over 7.8 billion people, alongside climate change. Chemistry plays a vital role in addressing these sustainability issues, yet traditional processes often waste non-renewable resources and generate pollution, opposing sustainability goals. This dilemma has promoted the emergence of Sustainable Chemistry, essential for creating solutions to these challenges. Green Chemistry, which prioritizes the design of chemical processes that minimize hazardous waste (Aacatid et al., 2021), complements this field by driving innovative technologies aimed at environmental restoration and discovering new materials to solve problems from current methods. Although obstacles remain in advancing Sustainable and Green Chemistry, they are crucial in education, research, and industry globally. They enhance our understanding of sustainability through green design and material processes. Scientific data supports national policies for sustainable development, including Malaysia's Vision 2020, emphasizing environmental concerns. The University of Malaya advances the Green Chemistry agenda to improve regional livability and confront global sustainability issues. The European Union and OECD recognize Sustainable Chemistry and circular economy principles. Green Chemistry enhances human health and environmental safety by reducing hazardous substances from the start (Aacatid et al., 2021) and offers economically viable solutions for better living standards through clean resources and safe environments. (Asif et al., 2019)

Keywords: Sustainable development, Green Chemistry, environments, sustainability.

1. Introduction

As the global population approaches eight billion, humanity faces the interconnected challenges of climate change, food and water scarcity, waste accumulation, pollution, and habitat destruction—challenges that threaten the delicate earth and society (Jen Mendelsohn Matus et al., 2013). Chemistry plays a pivotal role in the exploration and development of sustainable, green, eco-efficient, and non-toxic alternatives to fossil fuels, non-renewable materials, and hazardous compounds. The goal is not limited to short-term solutions. Scientists are called to innovate and re-think the trajectory of material production, processing, and consumption in order to design and implement necessary long-term solutions to achieve true sustainability.

Sustainability in chemistry refers to the complementary pursuits: “green chemistry” and “sustainable chemistry.” Goals in “green chemistry” focus on hazard reduction in the design of chemical products and chemical processes. The U.S. Environmental Protection Agency recognizes twenty principles to embody the objectives of green chemistry. Examples of green chemistry include the development of renewable feedstocks (alternatives to fossil-based materials) and the elimination of hazardous solvents (using water as a solvent instead). The goal of a green chemistry product idea is to have little or no hazard along the material or processing stage. “Sustainable chemistry,” on the other hand, pursues reframing material production, processing, and consumption to minimize energy and mass flow rate, specifically fossil resources and greenhouse gas emission, compared with renewable resources and non-greenhouse gases. The goal of sustainable chemistry is to achieve harmony in the earth.A robust “net zero” strategy recognizes that true sustainability comprises a “sustainable resource” principle and a “hazard-free” principle. The required grand strategies at earlier stages consider “renewability” and “non-toxicity” principles, reflecting the need to re-think development from the consideration of fossil, non-renewable, and toxic synthetic materials and products.

2. Foundations of Green Chemistry

The fundamental problem of contemporary chemistry lies in the vast amount of chemical substances synthesized. Every year, worldwide production and use generate trillions of grams of synthetic organic chemicals such as fuels, flavorings, fragrances, herbicides, insecticides, medi-cines, plastics, solvents, stabilizers, and surfactants. The estimated amount of synthetic organic chemicals used within the European Union is at least 103 kg per person. Based on a worl-dwide population of approximately 8 billion, and in consideration of the widespread use of organic chemicals by industries, hospitals, domestic households, and similar settings, the tentative estimate is on the order of 1014 grams per year. For the chemical sector, successful solutions have to be implemented to limit the accumulation of hazardous substances. Green Chemistry makes it possible to increase yield and reduce waste and other hazardous materials (Jen Mendelsohn Matus et al., 2013).

2.1. Atom Economy and Waste Prevention

Sustainable chemistry improves atomic efficiency, reduces waste and hazardous substances.

Atom economy determines how efficiently synthetic methods incorporate materials into a product. A green reaction maximizes atom economy by including a high proportion of raw material in the desired product. High atom economy minimizes hazardous waste produced and unsatisfactory by-products that necessitate further separation, purification, and disposal. Several global organizations, such as the American National Research Council and the Royal Society of Chemistry, endorse a similar green definition (Ta, 2018).

Waste prevention advocates avoiding or minimizing the generation of waste (BHANDARI, 2018). Accurate waste evaluation in research and industry has stimulated the development of semi-quantitative parameters to gauge process waste. The E-factor calculates the mass of waste by subtracting the mass of products recovered from the mass of raw materials. A low E-factor reflects greener reactions with maximum atoms incorporated into products and a minimal amount of unwanted materials. The E-factor is useful for tracking waste generation over time and comparing waste intensity across diverse organic transformations. It has spurred a concerted effort to boost atomic efficiency in chemical synthesis. The process mass intensity (PMI)—the mass of raw materials divided by the mass of the desired product—functions analogously to the E-factor and provides a complementary approach to waste assessment.

2.2. Safer Solvents and Reaction Conditions

Achieving green and sustainable chemical processes requires reducing toxicity of solvents and avoiding their use altogether through solid-state or solvent-free transformations (Miele et al., 2022).Toxicity represents a major determinant of solvent safety, and prioritizing non-toxic solvents reduces risks to health and the environment (Jordan et al., 2022). Extensive knowledge exists on toxicological properties of many chemical substances and relevant databases are readily available. However, even non-toxic solvents can frequently lead to significant exposure. The capability to reuse solvents reduces resource consumption and waste generation; therefore, ensuring that chosen solvents can be recycled enhances sustainability of a chemical process.

In addition to direct exposure, safety also encompasses flammability, reactivity, and potential for the formation of hazardous substances. Solid-state chemical transformations and fully aqueous reactions constitute nearly ideal approaches. Although organic reactants often remain essential, innovative aqueous and surfactant-assisted strategies can significantly diminish reliance on conventional organic solvents.

2.3. Energy Efficiency and Renewable Feedstocks

Recent decades have witnessed an unprecedented increase in energy consumption by the human race. More than half of the total primary energy consumption and two-thirds of the total greenhouse gas emissions come from the energy use within the industrial and transportation sectors. The chemical industry consumes substantial amounts of energy, and most chemical processes occur at high temperatures. Thus, if the industry still adopts traditional catalysts and energy sources, it is impossible to achieve sustainable development. Current energy inputs for chemical transformation mainly include thermal, electrical, and light energies. In addition to solar and wind energy, biomass has also emerged as an alternative energy input. The integration of biomass and chemicals has great potential to mitigate pollution and carbon emissions and advance integrated biorefineries towards sustainability (I. Meramo-Hurtado et al., 2020). The transition from fossil resources toward biomass feedstock via chemical, biological, or bioelectrochemical transformation is a fundamental constraint in developing both sustainable chemical industries and a circular bioeconomy (Liu et al., 2021).

3. Design and Evaluation of Green Chemical Processes

In a practical industrial setting, green chemical processes must not only be environmentally friendly but also economically viable. Process intensification, defined as the design of a chemical process that significantly reduces the required equipment size and capital cost while increasing productivity, is one strategy to leverage the integration of green chemistry into industrial processes (Ibrahim Samli, 2011). Compared to conventional designs, intensified designs can provide equivalent or superior chemical performance while using significantly less energy, as illustrated in Examples 1 and 2 (BHANDARI, 2018).

To enable such comparisons and provide guidance for process design, several metrics are available to quantify the greenness of a process from both a chemical and economic perspective. The E-factor (mass waste generated divided by mass of product sold) provides a measure of the mass efficiency of a process; lower values correspond to less waste, thereby increasing greenness, while higher values indicate higher environmental impact. Process-mass-intensity (PMI), the mass of raw materials consumed (excluding feedstock), similarly, offers a means of evaluating the overall efficiency of a process. Life-cycle-assessment (LCA) indicators further help to quantitatively assess the performance of chemical processes according to their energy, environmental, and resource sustainability profiles.

3.1. Process Intensification and Green Metrics

Process intensification (PI) comprises systematic modifications of chemical processes rendering them more compact and efficient, while maintaining or improving functionality such as yield or selectivity (Jen Mendelsohn Matus et al., 2013). Despite PI's benefits, conventional design-oriented metrics of mass and energy efficiency remain applicable and relevant, thus hindering accurate assessment and comparative evaluation. PI processes have been reported with E-factors from 0.1 to over 100, and values even greater than 200 are plausible. Under such circumstances, additional process metrics are required. Understanding the origin of these massive differences is essential to ensure meaningful analysis of process alternatives. The following metrics help identify design directions toward greater intensification: • E-factor • PMI • Life-cycle assessment (LCA) indicators In addition to evaluating process alterations, complementary assessment of inherent reliability and risk of failure. While LCA addresses net resource and energy demand and associated environmental and health impacts, it does not quantify uncertainty; risk assessment frameworks—such as hazard, operability, reliability, and safety analysis (HORS)—fill this gap. The comprehensive, integrated framework combines diverse environmental concerns into consistent analysis, identifying optimal intensification approaches through reliable outcome predictions.

3.2. Life Cycle Assessment and Risk Assessment: Life cycle assessment (LCA) evaluates the environmental impacts of products or processes across their entire life cycle, from raw material extraction to disposal. The analysis typically encompasses multiple impact categories, including climate change, ozone depletion, resource depletion, human toxicity, and ecotoxicity. LCA is often combined with stakeholder analysis to enhance socio-economic evaluations. However, LCA approaches require careful selection of life-cycle stages, processes, and impact categories based on scenario specificities, and many LCA implementations lack sensitivity assessments of underlying data, modelling, and assumptions (Mitchell et al., 2013). Risk assessment frameworks consider hazards, exposure, and risk throughout the life cycle of products, processes, or technologies; life cycle stages addressed often extend beyond a confined scope of impacts like climate change or resource depletion. A decision-analysis structure presently employs LCA and early design hazard and exposure frameworks within a risk-assessment context, enabling consideration of life-cycle information across impact categories and of chemicals, products, and processes whose risk profiles might be evaluable despite incomplete datasets.

3.3. Circular Economy and Material Sustainability

Dave et al. identify inherent hazards associated with chemical products as a major barrier impeding adoption of sustainable and green chemistry practices. Although progress has been made to reduce environmental impacts by targeting more benign feedstocks, safer products and materials remain a key challenge. Sustainability challenges have led to the sharing economy model, which requires access and material, and therefore depends on efficient design for sustainability principles like circularity, durability and repairability (Peck et al., 2020).

The global development of an environmentally sustainable circular economy, after the initial linear economy model, has gained great importance. Currently, used products can be exported (to capture some recovery value) or transformed to bulk recyclable resins, but recycling back to intermediate chemistries is theoretically possible with significant research or development. However, even if recycling technology can advance to this stage, a key problem arises: the sorting procedure and line-of-ingredients stage typically remain almost unchanged in all commercial production from feedstock supply to factory operation, which is not compatible with circular economy requirements. Initially, many different types of recycled plastics and non-plastics were not able to be mixed because none was compatible with the other. Gradually, independent grades were developed and retained for local recycling and resale, which made recycling more effective; yet the color impurity remained still. Nowadays, local recycling capacity of some limited resin types was challenged, resulting in no economically attractive recovered-resin recycling processing routes—therefore, numerous amounts were still disposed after the recovery step but were lost forever.

4. Green Catalysis and Sustainable Synthesis

“In the quest for sustainability, catalysis has much to offer when considered from a fundamental science perspective. Carbon-free societies, reduced GHG emissions, the ubiquitous need for renewable energy conversion and storage, and the general availability of chemical feedstocks from C1 compounds provide much impetus for investments in catalyst science. These imperatives demand that catalysts be developed that enhance access to complex structures by shortening synthetic steps; that lower energy barriers associated with reactions or separations; that provide for selective access to valuable compounds; that are safe to use; and that are benign, or at least less damaging, to the environment. Two broad classes of sustainable catalysis are biocatalysis and heterogeneous catalysis. Both sustain critical societal functions, and both merit serious consideration by chemists addressing sustainability. Emerging fields such as electrocatalysis and photocatalysis have the potential to profoundly modify the way energy is harnessed and used, but they remain in their infancy. Much fundamental research is still needed to meet both academic and commercial objectives and to enable balanced evaluation of their broader sustainability." (García-Álvarez, 2020)

4.1. Catalyst Design and Selectivity

Catalyst design remains central to contemporary green chemistry, owing to widespread ecological concerns regarding energy utilization and raw material exploitation for synthetic processes (Corma Canós, 2016). Sustainable catalysts alter performance parameters to align chemical innovations with environmental standards. Sustaining an environmentally acceptable chemical procedure mandates catalyst activity, selectivity, turnover, and lifetime be majorly optimized. Catalyst activity, the primary parameter, governs the number of chemical conversions produced over any timeframe; hence, it represents the immediate means of assessing process environmental perspective. Greener catalysts augment reaction selectivity between desired products and offensive by-products. Polluting, hazardous, or unaffordable compounds preclude achieving green chemistry principles in specific applications. Maximizing selectivity constitutes pivotal bounds in eco-metric expanded, over and above general greener procedure and permit alterations in gaseous pollutant associated in conditions of chemical synthesis associated with existing material; therefore turnover enacts an auxiliary character of efficiency measure and pollutant ordinate.

4.2. Biocatalysis and Enzyme Engineering

Enzyme-based routes can improve the environmentally friendly for chemical synthesis and can address the issues of activity loss due to harsh reaction conditions or solvents. Biocatalytic chemistry can provide attractive alternatives for the discovery and design of potential new chemical entities with substantially reduced overall environmental impacts (Domínguez de María & Hollmann, 2015). Compared to synthetic methods, namely, total chemical synthesis, these semi-synthetic approaches exhibit a significantly improved environmental profile. They are termed chemo-enzymatic and biocatalytic processes, respectively, according to their catalytic organization. On a mass, energy, or overall process significance basis, biocatalytic routes can offer enhanced sustainability compared to their total synthetic counterparts (Wohlgemuth, 2011). The incorporation of an enzyme-based step involves a comparative between the catalytic processes has demonstrated a scale-through the enzymes even those having no direct synthetic utility.

Catalysts are critical components of all chemical processes and presently, biocatalyst have entered a maturity stage, being widely applied in both fine and bulk chemistry. More than 300 licensed biocatalytic processes exist in industry, ranging from esters, amino acid, and carbohydrates to biofuels and trifluoromethylation manufacture (Basyaruddin Abdul Rahman, 2010). Compared to homogeneous and heterogeneous chemical catalysts, biocatalysts present a higher selectivity toward even challenging organic transformations. Other advantages afforded by biocatalysts and enzyme-based reactions include the processing of substrates that were difficult or impossible to utilize via chemical catalyst, zero-corrosion for the reactor material, drop-in interchangeability, and the construction of multifunctional and complex target molecules or precursors.

4.3. Electrocatalysis and Photocatalysis

The electrochemical energy transition involves replacing fossil fuels with electricity from renewable resources, enabling the sustainable transformation of biomass or CO2 into biobased or fossil-free chemicals, and promoting the circular economy. Through conventional catalytic technology, this goal is pursued via the chemical hydrogenation of compounds derived from biomass or CO2. This process consumes hydrogen, derived from the electrolysis of water, or other low-value compounds, resulting in the need for more sustainable hydrogen generation alternatives. Electrocatalysis offers the potential to utilize electricity from renewable resources and to couple the upgrading of biomass or CO2 directly with their formation, thereby avoiding hydrogen capture and maximizing the overall carbon efficiency of the process. Liquid fuels allow for long-term energy storage, but the development of dedicated catalytic pathways for the production of such commodity grade chemicals from biomass and CO2 continues to lag behind (Kaeffer & Leitner, 2022).

While light-driven catalytic processes are predominantly linked to the field of photocatalysis, the investigation of electrocatalytic routes in conjunction with solar-driven approaches shares common major “themes,” such as the selection of proper light-harvesting systems, redox mediators, and catalysts. Photocatalytic systems and their electrode-driven counterparts offer alternatives for compound production from CO2 and biomass-derived precursors, as reflected in the current progress of systems permitting the coupling of the formation of biofuels or related chemicals with the conversion of either CO2 or biomass (Papanikolaou et al., 2022).

5. Green Analytical Chemistry

Green analytical chemistry focuses on environmentally friendly methods to minimize hazardous waste and energy use. It supports sustainable practices by advocating less toxic reagents, energy-efficient procedures, and renewable resources in analytical processes. The aim is to reduce the environmental impact of chemical analysis while ensuring accuracy and reliability. Analytical chemistry is crucial in research and quality control across fields like food, environmental, pharmaceutical, forensic, and industrial analysis. Key objectives of analytical methods include selectivity, sensitivity, accuracy, and speed. Often, the use of analytical reagents is necessary.

Developing better analytical methods that align with green chemistry principles requires careful assessment of reagent amounts and material safety. Many scientists are now aiming to blend sustainable practices with analytical techniques. Current analytical chemistry not only focuses on improving detection limits and speed but also considers waste generation and hazardous reagent use. Sustainable analytical chemistry seeks to lower the consumption of chemicals and resources in analysis. For effective extraction of bioactives from red algae and Spirulina platensis, eco-friendly and less hazardous solvents are preferred. Extraction is performed at room temperature using renewable solvents such as ethyl oleate. CO2 and 2-propanol are considered green solvents, while propan-1-ol and ethyl acetate are toxic. Ethyl oleate extraction proves more effective than CO2 and 2-propanol for various algal types, including Phaeophyceae and Chlorophyceae. Green solvents are defined as biodegradable, non-hazardous, and renewable materials. (Asif et al., 2019)(BHANDARI, 2018)

5.1. Minimization of Reagents and Sample Preparation

Reagent use and sample preparation are two principal challenges in green analytical chemistry (Kissoudi & Samanidou, 2018). Consequently, implementation of fewer reagents and reducible sample preparation benefits analytical chemistry generally. Particularly, reducing reagent usage minimizes laboratory hazards, especially for toxic or hazardous substances, and avoids hazardous waste generation (Lee & Marrocchi, 2024). To address sample preparation, extensive efforts can facilitate more straightforward, accelerated processes.

5.2. Solventless and Green Extraction Methods

Many modern analytical procedures need sample preparation, which mostly involves the extraction of target components. Solvent extraction, which is one of the most versatile and effective extraction methods, usually requires the use of large amounts of organic solvents. To mitigate this undesirable effect and make solvent extraction greener, green-extraction methods have been developed. Solvent-free extraction or dry extraction is focused on solid samples in which macromolecules containing valuable organic compounds such as oils, pigments, or antioxidants can be extracted without solvents. Extraction of these compounds is possible due to the presence of organic extractive materials on the surface of the samples and extracts based on solid-solid interactions between the sample and the extractive materials. These interactions can be distinctly different from solvent extraction, whereby the extraction depends on the organic solubility and different amounts of extractive compounds can be collected within the same period of time (Dharmarajan, 2019).

Another green-extraction concept is in-cell extraction during which the extraction takes place inside the sample vial. In-cell extraction has been applied for extraction of the polar compound caffeine from green tea and other polar compounds from TCM (traditional Chinese medicine) samples. Conventional sample pre-treatment such as filtration, centrifugation and dilution could totally be avoided with in-cell extraction and further clean-up can be achieved inherently with integrated solid-phase extraction.

5.3. Instrumentation with Reduced Energy and Waste

Analytical chemistry, essential across numerous applications, generates hazardous wastes that must adhere to regulations. Thus, adopting a green-analytical approach is crucial. The goal is to minimize resource consumption and waste generation without sacrificing the quality of analytical results (Asif et al., 2019).

Strategies include utilizing low-energy detectors, fully recyclable consumables, impeded routine analyses of volatile analytes, and ensuring that non-trace analyses undergo the same amount of sample preparation as trace analyses. Designing instruments to help avoid waste increase is highly beneficial for analyses of all natures ().

Exploiting pre-existing detection principles, relying on the passive operation of the detector and/or designing the instrument to execute sampling and analysis exclusively when a signal is not detected are additional valuable solutions.

6. Industrial Case Studies and Policy Context

Sustainable practices are increasingly adopted across various industries, paving the way for impactful policies in chemical manufacturing. Regulatory incentives focused on sustainability and waste reduction are now part of the chemical policy framework. The Green Chemistry Challenge Awards showcase successful implementations and common obstacles. At local, state, and national levels, policies are being established to promote materials conservation, energy savings, and waste minimization, all while integrating sustainability principles. Regulations addressing health and environmental hazards are being implemented across various government levels. Internationally, companies are committing to green chemistry initiatives highlighted in the U.S. Environmental Protection Agency's (EPA) awards, which recognize innovative methods that lower hazardous materials and waste, offer safer product alternatives, improve yield, or enable efficient green product manufacturing. Innovations include using fewer hazardous chemicals and producing biodegradable lubricants and safer solvents, enhancing synthesis productivity through catalysis. Pharmaceutical designs also aim to minimize environmental impact while enhancing efficiency, including applications like catalytic reuse of hydrogen and production of valero-lactam from phenol for markets in caprolactam and cyclohexanone. Each chemical sector defines mechanisms for greener processes using specific criteria. Programs aimed at high-priority sectors assess overall performance through both qualitative and quantitative indicators. While assessing chemistry performance remains complex, stepwise indicators are clarifying material flow impacts across product life cycles. Practitioner collaborations drive regulatory actions, bolstering federal investments in green chemistry that align with stakeholder goals. The federal Green Chemistry Initiative coordinates interagency efforts to promote greener chemistry, addressing research barriers, providing outreach, engaging early-stage ventures, and fostering public-private partnerships, thereby facilitating transitions to resource-efficient innovations. (Matus et al., 2017)

7. Challenges, Gaps, and Future Directions

The pursuit of sustainable development is increasingly global in scope, manifested through the concept of sustainability. The aim of sustainable development is to balance the needs of society and the economy with the protection of the environment, such that the aspirations of future generations are not compromised. As a scientifically based approach, sustainability can be defined in terms of resources and impact, namely, making use of renewable resources, maintaining a stable concentration of pollutants in the environment, and enabling recovery of non-renewable resources. A scientific-based approach to assessing sustainability continues to emerge (Matus et al., 2017). Sustainable development seeks to balance the considerations of society, economy and environment; sustainable development of the chemical industry is addressed through promotion of green chemistry. Green chemistry embraces a set of principles designed to encourage the development of inherently safer chemical products and processes that reduce toxicity and avoid the generation of hazardous substances to prevent negative impacts on human health and the environment from cradle to grave (Jen Mendelsohn Matus et al., 2013). Implementing the sustainable chemistry/green chemistry paradigm widely poses significant challenges at the institutional, cultural, and infrastructural levels. The need to address these challenges is underscored by the scale of chemical manufacture and the consequent massive volume of waste produced globally.

8. Conclusion

A comprehensive vision for sustainable green chemistry is examined to meet societal and economic expectations. The Chemistry community is primarily driving these efforts, focusing on viable chemical production methods and compliance with policies regarding hazardous pollutants. The advancement of high-impact, green chemistry innovations across Chemical research and Engineering is essential. Recognizing sustainable innovation along the entire chemical production cycle—including processes, products, performance, degradation, recovery, and systems—is urgent. The development of safe-by-design innovations aligns with mandatory sustainability assessments. Tackling these priorities is crucial for achieving true Sustainability and Sustainable Development through Chemistry and Chemical Engineering, which would spur community engagement and accelerate progress. The philosophy of Chemistry and its collective goals emphasizes sustainable, non-toxic materials for future generations and current citizens. This also encourages philosophical reflection and draws lessons from past global synthesis challenges, such as the "Holy Grail" labels for liquid fuels.

9. References:

- Asif, M. A., & Touquir Alam, M. D. (2019). An Overview on Execution of Green Chemistry as an Alternative Technique in Organic Synthesis.
- Jen Mendelsohn Matus, K., C. Clark, W., T. Anastas, P., & B. Zimmerman, J. (2013). Barriers to the Implementation of Green Chemistry in the United States.
- Ta, L. (2018). N-Heterocyclic Carbene Catalysis in Organic Synthesis - A Green Chemistry Approach.

- BHANDARI, S. U. N. E. E. T. A. (2018). APPLICATIONS OF GREEN CHEMISTRY PRINCIPLES IN AGRICULTURE.
- Miele, M., Pillari, V., Pace, V., R. Alcántara, A., & de Gonzalo, G. (2022). Application of Biobased Solvents in Asymmetric Catalysis. ncbi.nlm.nih.gov
- Jordan, A., G. J. Hall, C., R. Thorp, L., & F. Sneddon, H. (2022). Replacement of Less-Preferred Dipolar Aprotic and Ethereal Solvents in Synthetic Organic Chemistry with More Sustainable Alternatives. ncbi.nlm.nih.gov
- ○ Meramo-Hurtado, S., Sanchez-Tuiran, E., María Ponce-Ortega, J., M. El-Halwagi, M., & Angélica Ojeda-Delgado, K. (2020). Synthesis and Sustainability Evaluation of a Lignocellulosic Multifeedstock Biorefinery Considering Technical Performance Indicators. ncbi.nlm.nih.gov
- Liu, X., Yu, D., Yang, W., Zhang, Q., Wu, H., & Li, C. (2021). Development of Sustainable Catalytic Pathways for Furan Derivatives. ncbi.nlm.nih.gov
- Ibrahim Samli, A. (2011). Evaluation of Chemical Processes for Sustainable Optimization.
- Mitchell, J., Pabon, N., A. Collier, Z., P. Egeghy, P., Cohen-Hubal, E., Linkov, I., & A. Vallero, D. (2013). A Decision Analytic Approach to Exposure-Based Chemical Prioritization. ncbi.nlm.nih.gov
- Peck, P., Luth Richter, J., Dalhammar, C., Peck, D., Orlov, D., Machacek, E., Gillabel, J., L.K. Nußholz, J., Wrancken, K., Whalen, K., Modis, K., Milios, L., Messing, M., Bocken, N., Tojo, N., Davris, P., Manshoven, S., Sfez, S., Lindhqvist, T., & Voytenko Palgan, Y. (2020). Circular Economy - Sustainable Materials Management : A compendium by the International Institute for Industrial Environmental Economics (IIIEE) at Lund University.
- García-Álvarez, J. (2020). Special Issue: "Advances in Homogeneous Catalysis". ncbi.nlm.nih.gov
- Corma Canós, A. (2016). Heterogeneous catalysis: understanding the fundamentals for catalyst design.
- Domínguez de María, P. & Hollmann, F. (2015). On the (Un)greenness of Biocatalysis: Some Challenging Figures and Some Promising Options. ncbi.nlm.nih.gov
- Wohlgemuth, R. (2011). Molecular and Engineering Perspectives of the Biocatalysis Interface to Chemical Synthesis.
- Basyaruddin Abdul Rahman, M. (2010). Haute couture: molecules and biocatalysts.
- Kaeffer, N. & Leitner, W. (2022). Electrocatalysis with Molecular Transition-Metal Complexes for Reductive Organic Synthesis. ncbi.nlm.nih.gov
- Papanikolaou, G., Centi, G., Perathoner, S., & Lanzafame, P. (2022). Catalysis for e-Chemistry: Need and Gaps for a Future De-Fossilized Chemical Production, with Focus on the Role of Complex (Direct) Syntheses by Electrocatalysis. ncbi.nlm.nih.gov
- Kissoudi, M. & Samanidou, V. (2018). Recent Advances in Applications of Ionic Liquids in Miniaturized Microextraction Techniques. ncbi.nlm.nih.gov
- Lee, J. & Marrocchi, A. (2024). Advances in green chemistry and engineering. ncbi.nlm.nih.gov

- Dharmarajan, S. (2019). Evaluating Green Solvents and Techniques in Extraction Methods.
- Matus, K., T. Anastas, P., C. Clark, W., & Itameri-Kinter, K. (2017). Overcoming the Challenges to the Implementation of Green Chemistry.

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