WORLD JOURNAL OF PHARMACEUTICAL RESEARCH
SJIF Impact Factor 8.084
Volume 12, Issue 21, 1145-1165. Review Article ISSN 2277– 7105

AN OVERVIEW ON GREEN CHEMISTRY

Dhokare Pratik Dnyandev*, Dr. Megha Salve and Prof. Shete Abhijeet

Shivajirao Pawar College of Pharmacy Pachegaon Dist – Ahmednagar, Maharashtra 422602.

Article Received on
20 Oct. 2023,
Revised on 10 Nov. 2023,
Accepted on 30 Nov. 2023
DOI: 10. 20959/wjpr202321-30489

***Corresponding Author**
Dhokare Pratik Dnyandev
Shivajirao Pawar College of Pharmacy Pachegaon Dist – Ahmednagar, Maharashtra 422602.

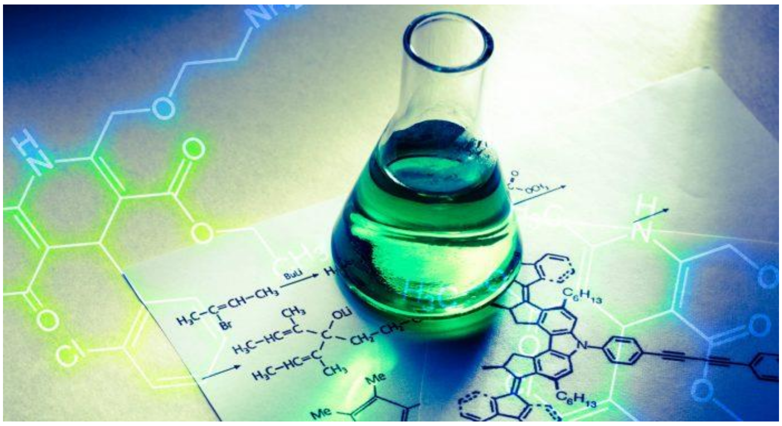
ABSTRACT

Over the past decade, there has been significant interest in a field that leverages chemical innovation to achieve both environmental and economic goals. In an ideal scenario, a successful business would excel in both affordability and reputation, creating an ideal world. To determine a company's competitive advantage, one can examine either those offering rare products or those with the lowest prices, with the eventual victor being the one that prevails. The efficiency of a pharmaceutical company's manufacturing infrastructure is pivotal for its success when transitioning from acute to chronic treatment markets. Understanding a company's customers' mobility requirements provides valuable insights for operational improvements.[1] Account segmentation is a valuable method for evaluating these needs. In the 1990s, Paul Anastas and John Warner introduced the 12 principles of Green Chemistry, emphasizing the reduction or elimination of toxic solvents and waste in chemical processes. A key focus of Green Chemistry research is the development of eco-friendly analytical methodologies, known as Green Analytical Chemistry.

KEYWORDS: Green Chemistry, Chlorophyl, Novelty, Sustainablity, Pharmaceuticals.

INTRODUCTION

Green chemistry, as defined by the Environmental Protection Agency (EPA), is a discipline focused on designing chemical products and processes that are environmentally friendly by reducing or eliminating the use of hazardous substances. This concept emerged in the early 1990s and has gained international recognition, with numerous programs and government initiatives worldwide, particularly in the United States, United Kingdom, and Italy.[2]



Central to green chemistry is the idea of intentional design. It involves creativity, careful planning, and systematic thinking. The Twelve Principles of Green Chemistry serve as guidelines to assist chemists in achieving sustainability goals.

The essence of green chemistry is to promote sustainability at the molecular level, and it has found applications across various industries, including aerospace, automotive, cosmetics, electronics, energy, household products, pharmaceuticals, and agriculture. Many successful examples highlight how this approach can yield economically competitive and award-winning technologies that are both profitable and environmentally responsible.

In the latter part of the 20th century, there was a growing global concern regarding the environmental impact of various industries. Issues such as acid rain, greenhouse gas emissions, water pollution from fertilizers, urban pollution, and ozone layer depletion became prominent. While some of these problems were associated with power generation and transportation, which extended beyond the chemical industry's direct control, the emergence of green chemistry addressed a crucial aspect of industry's role in environmental sustainability.[3]

❖ Green Chemistry

The color green symbolizes both chlorophyll in nature and the dollar in finance. The concept of "going green" has become a central point of contention for environmental activists, and it has also evolved into a prominent trend in product marketing. Furthermore, for chemists, embracing the principles of green chemistry is now a critical imperative, impacting all aspects of the chemical sciences, from fundamental research to applied practices, production, and education.

Green chemistry isn't a distinct scientific field but rather a holistic interdisciplinary approach rooted in chemical, ecological, and social responsibility. This approach fosters creativity and drives innovative research.[4] It serves as a driving force in finding and maintaining a delicate equilibrium between the use of natural resources, economic progress, and environmental preservation.

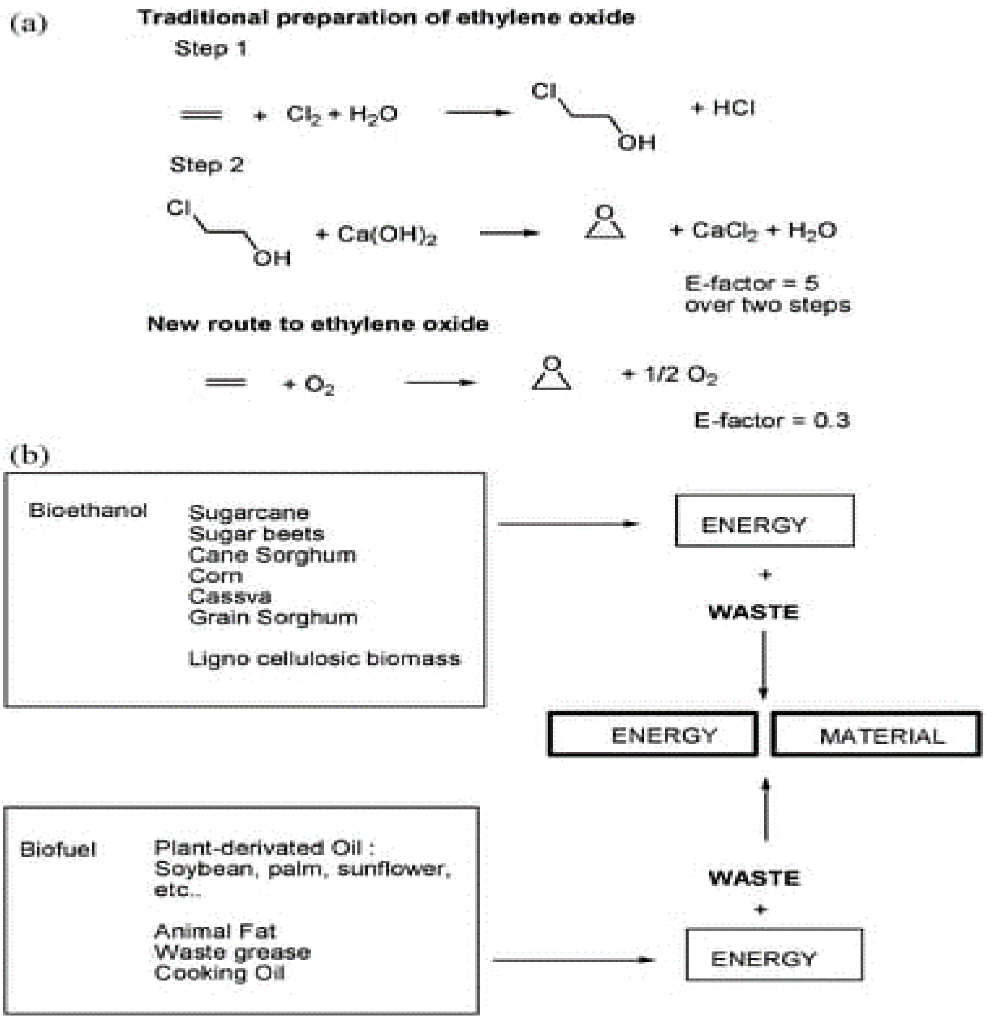
❖ **Principle**

1. Waste

The primary principle of Green Chemistry emphasizes waste prevention as the first step. It is far more effective to avoid waste generation rather than dealing with cleanup afterward. Waste can come in various forms and can have different environmental impacts, depending on its characteristics, toxicity, quantity, and release method. When a substantial portion of raw materials is lost due to the initial process design, it inevitably leads to undesirable waste.

In 1992, Roger Sheldon introduced the concept of the Environmental Impact Factor, known as the E-Factor. This metric quantifies the amount of waste generated per kilogram of product, serving as a measure of the environmental sustainability of a manufacturing process. This factor has highlighted the inefficiency of certain industrial processes and encouraged the exploration of innovative solutions.

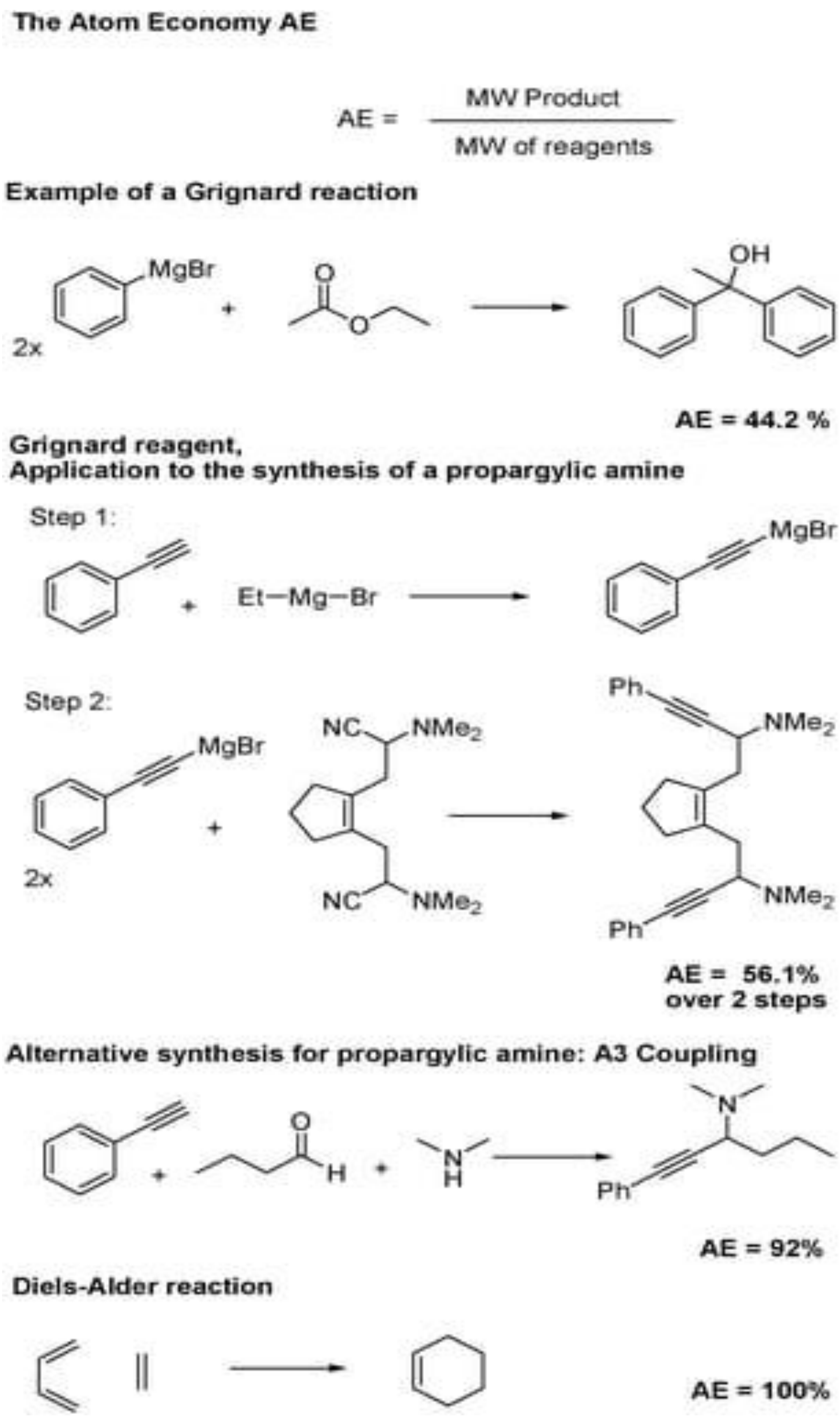
For example, consider the early synthesis of ethylene oxide, which used a chlorohydrin intermediate and had a high E-Factor of 5, resulting in 5 kilograms of waste for every kilogram of product. This calculation doesn't even account for the waste water contaminated by chlorine by-products. By modifying the synthesis to use molecular oxygen, eliminating the need for chlorine, the E-Factor dropped significantly to only 0.3 kilograms of waste per kilogram of product.[5] This new process reduced waste generation by more than 16 times and eliminated the production of waste water as well.



In cases where the generation of byproducts is unavoidable, it's essential to explore innovative solutions. One productive approach is to embrace industrial ecology, where waste materials can be transformed into valuable raw materials for other processes as they re-enter the production cycle. This concept is currently being implemented in the field of biofuel production.

2. Atom economy

In 1990, Barry Trost introduced the concept of synthetic efficiency, known as Atom Economy (AE) or Atom Efficiency. Atom Economy focuses on optimizing the utilization of raw materials to ensure that the final product contains the maximum possible number of atoms from the initial reactants.[6] The most ideal reaction would involve incorporating all atoms from the reactants into the final product. Atom Economy is quantified as the ratio of the molecular weight of the desired product to the total molecular weights of all reactants used in the reaction. This metric serves as a theoretical value to quickly evaluate the efficiency of a given reaction.

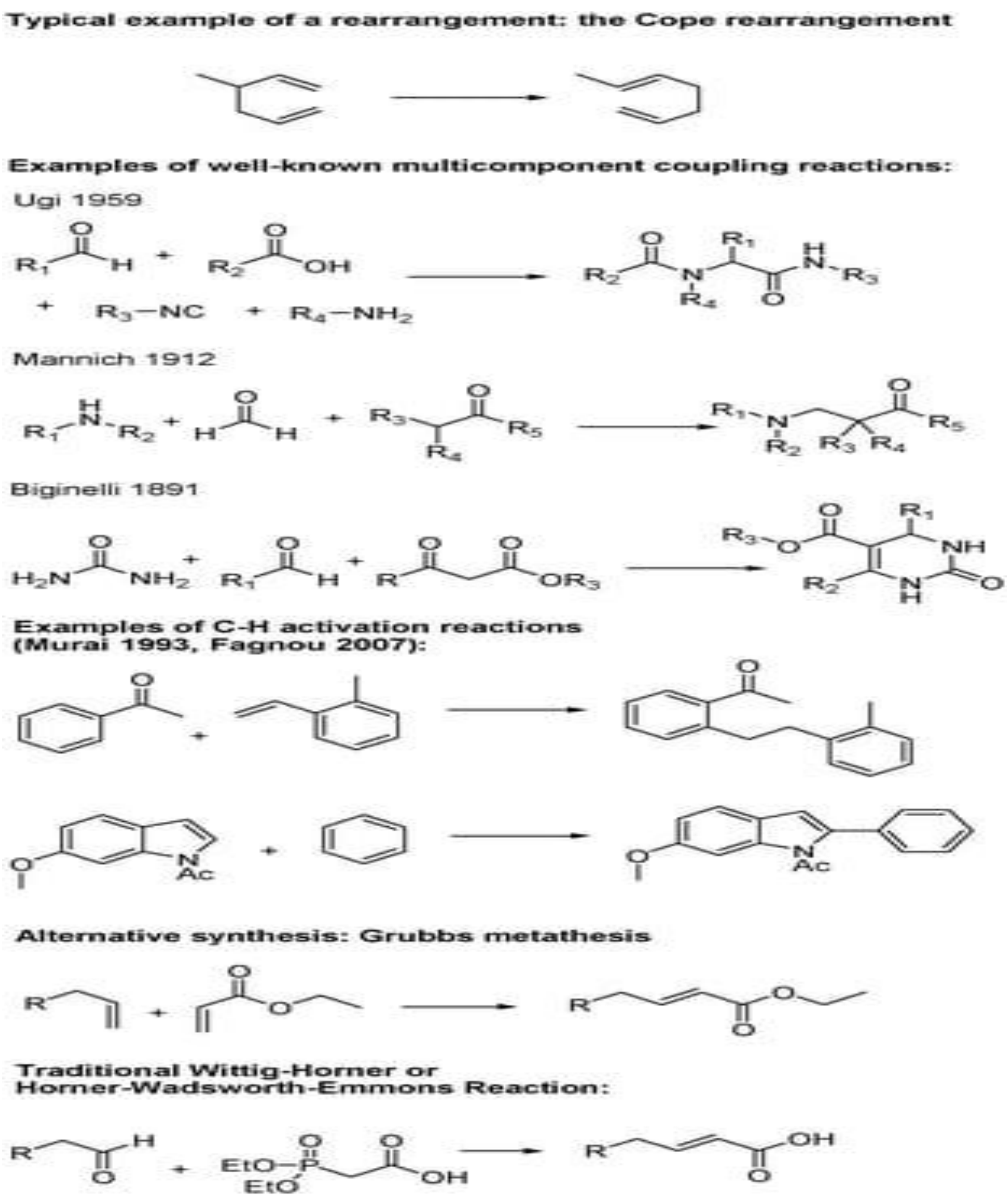


To illustrate this concept, let's examine a few examples, including the Grignard reaction, A3 coupling, and the Diels-Alder reaction. The Grignard reaction, well-regarded in organic synthesis, unfortunately falls short in terms of atom efficiency due to the use of a stoichiometric amount of metal reactant and the need to prepare the Grignard reagent separately. See Fig. 4 for a typical Grignard reaction and an application of the Grignard reagent to construct a propargylic amine type structure. In this case, the Atom Economy (AE) values are 44% and 56%, indicating a loss of half of the raw material. A more efficient solution was proposed by C.-J. Li and others in 2002 through the A3 coupling (Alkyne, Aldehyde, and Amine). This one-step, multi-component coupling reaction preserves atoms much better, with 92% of the original atoms used ending up in the final product.[7] The Diels-Alder reaction is another excellent example of an atom-economical reaction. It achieves an AE of 100% because it incorporates all atoms from the reactants into the final product. Diels-Alder reactions fall into the category of cycloaddition, which is considered one of the environmentally friendliest types of reactions in traditional chemistry.

3. Synthesis

As depicted in Fig. 5, organic chemists' toolbox has seen a significant expansion through innovative work. Many of the new reactions developed in the past decade complement the existing eco-friendly reactions discovered in the previous century. Reactions rooted in cycloaddition, rearrangement, or multi-component coupling were already well-established and represent one category of efficient reactions. Recently, there have been developments in cascade or tandem reactions, C-H activation, metathesis, and enzymatic reactions, all of which serve as cleaner and more efficient synthetic methods for organic chemists.[8]

For instance, the Grubbs catalyst facilitates alkene metathesis, operating through a mechanism similar to Wittig-type reactions like the Horner-Wadsworth-Emmons reaction, which involves the formation of a four-membered ring as a reaction intermediate. This catalyst is indispensable for building larger molecules. Importantly, unlike the Wittig reaction, metathesis doesn't generate a significant amount of waste. In the case of the Wittig reaction, the formation of phosphonium salts is unavoidable, as it's an inherent part of the reaction's design and serves as a primary driving force.[9]



C-H activation is a relatively recent and promising area of chemistry that holds great potential for the future. In traditional coupling reactions, activated carbon-halogen bonds are typically used due to their high reactivity. However, this approach often necessitates additional steps to produce the halogenated precursor, which is not commonly found in nature. The shift to C-H activation in lieu of traditional coupling reactions eliminates the requirement for halogenated precursors and, as a result, reduces the generation of halogenated waste byproducts.

Two notable examples of C-H activation stand out. In 1993, Murai and colleagues used a ruthenium catalyst to couple inactivated substrates like acetophenone and 2-methylstyrene, marking a significant milestone in the field and representing one of the early instances of C-H activation. In the second case, in 2007, Fagnou and Stuart achieved selective coupling of two aromatic compounds without the need for activating or directing groups. These examples highlight the transformative potential of C-H activation in advancing the principles of Green Chemistry.[10]

4. Molecular Design

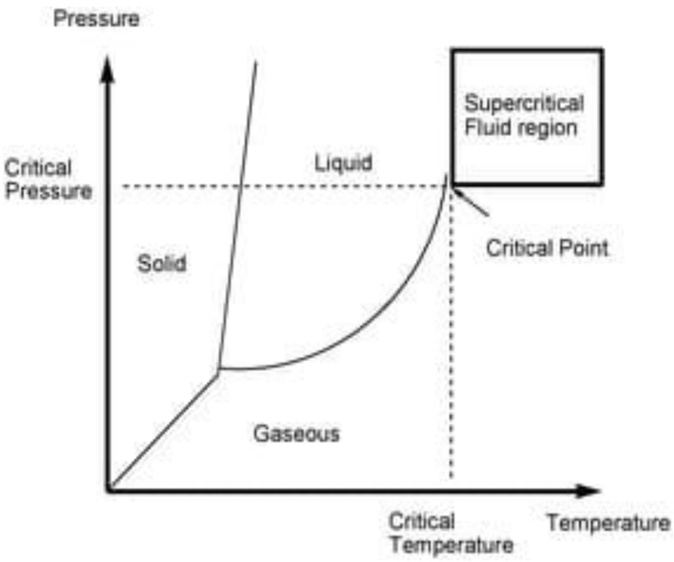
While there has been substantial emphasis on designing chemicals for a wide range of applications, from medicines to materials, there has surprisingly been little attention given to considering hazards in the design process. It is crucial to understand the properties of a molecule that impact the environment and how these substances transform in the biosphere to ensure sustainability. With a comprehensive understanding of these aspects, chemistry can genuinely create molecules that are both safer for humans and the environment. Earlier work by Ariëns in 1984 and Garrett and Devito in 1996 demonstrated the necessity and feasibility of designing safer chemicals for the advancement of Green Chemistry.[11]

In recent decades, toxicology has evolved from a purely descriptive science to one with a strong mechanistic component and, more recently, an incorporation of in-silico methods. This transformation has enabled the development of correlations, equations, and models that link chemical structure, properties, and function. These approaches provide a foundation for the development of a comprehensive design strategy. For example, existing knowledge in medicinal chemistry can already offer valuable insights for establishing guidelines to design fewer toxic chemicals, incorporating specific features that prevent their harmful effects in humans and various animal organisms.

5. Solvents

Solvents have emerged as a prominent focus in Green Chemistry research. They pose a significant challenge in this field because they frequently contribute to the majority of wasted mass in syntheses and processes. Furthermore, many traditional solvents are characterized by toxicity, flammability, and corrosiveness. Their volatility and solubility have led to environmental pollution in the air, water, and land, increased risks of worker exposure, and even caused serious accidents. When recovery and reuse are feasible, it often involves energy-intensive distillation and the potential for cross-contamination. In an attempt to overcome these issues, chemists have been exploring safer alternatives. Solventless systems, water, supercritical fluids (SCF), and more recently, ionic liquids, represent some of the innovative "green" solutions.

Ideally, the best approach is to avoid using any solvent whenever possible because the inclusion of a solvent always necessitates efforts and energy to remove it from the system. Consequently, substantial efforts have been directed toward developing solventless systems. This concept gains support from the fact that solvents are responsible for most of the industrial waste.[12] Depending on the physical properties of the reagents used and the desired outcome of the transformation, this approach often requires new or redesigned chemistry to enable reactions to proceed without the original solvent.



Supercritical fluids (SCF) are derived from substances such as water, carbon dioxide, methane, methanol, ethanol, or acetone. Carbon dioxide, in particular, has become a widely used SCF, known as scCO2, which has proven to be a versatile, safe, and easy-to-handle solvent, as demonstrated by the work of Poliakoff, Leitner, Jessop, DeSimone, and others.[13] What makes SCFs, and scCO2 in particular, attractive is the change of state that occurs when the vessel is cooled or pressure is reduced. Above their critical points, SCFs become liquids suitable for performing reactions, and below, they become gases. By degassing the system, it's possible to completely remove the solvent. scCO2 has found various industrial applications, including the decaffeination of green coffee beans and the replacement of perchloroethylene in dry cleaning. Overall, supercritical fluids have proven to be a valuable alternative to traditional solvents.

Ionic liquids, pioneered in modern times by Seddon, are another example of environmentally friendly solvents. Ionic liquids, sometimes called room temperature ionic liquids, are liquid salts at room temperature. They have virtually no vapor pressure and are highly non-flammable.[30] A recent discovery by Jessop and others is the concept of a "switchable" ionic liquid, or a "smart-obedient solvent" that can be generated in situ, much like liquid scCO2. By adding pressurized carbon dioxide to an organic mixture, it transforms into an ionic liquid, creating a safer solvent in situ. Releasing the pressure reverses the process, turning the ionic liquid back into the original mixture, thus completely removing the solvent and eliminating the need for tedious purification and extraction steps.

Another example based on a similar concept is the development of fluorous biphasic catalysis pioneered by Horvath. A fluorous phase or solvent containing a catalyst suitable for the desired transformation is typically immiscible with organic reagents at ambient temperature.[14] However, when heated, they form a single phase, allowing the reaction to proceed. Upon cooling, the organic phase and the fluorous solvent separate, simplifying the purification process. This approach is appealing but comes with the limitation that fluorous solvents are expensive.

These examples highlight one of the significant challenges in chemistry, which is the separation of solvents from the desired product. Unless solventless systems are used, these improved green solvents are still auxiliary and must be isolated from the final product. Thus, when choosing an appropriate solvent, the issue of separation must be taken into consideration.

6. Energy

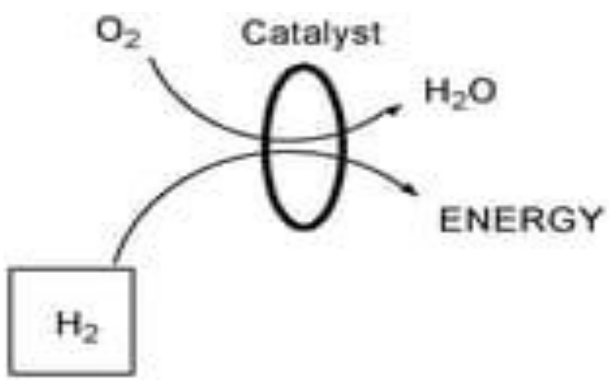
Escalating concerns about the depletion of petroleum resources and the surging energy consumption have driven the pursuit of more energy-efficient processes and the exploration of renewable energy sources that do not deplete rapidly in human-relevant timeframes.[15]

As mentioned in the initial section (first principle), unutilized energy can be seen as a form of waste. Designing chemical reactions and systems that minimize energy-intensive requirements is highly desirable. Chemists can reduce the energy barrier of chemical reactions or select appropriate reactants, allowing transformations to occur at room temperature. This reduction in energetic demands brings numerous direct and indirect benefits.

Enhancing the energy efficiency of chemical systems is just one part of the solution. The utilization of alternative energies is equally crucial. Various renewable energy sources have been identified, including biofuels, solar power (both thermal and photovoltaic), wind power, hydro power, geothermal energy, and hydrogen fuel cells. Green chemists play a vital role in this new challenge by designing both energy-efficient transformations and materials or chemical systems capable of harnessing these renewable energy sources.

Solar energy, as Earth's primary sustainable energy source, is a significant alternative to petroleum. Extensive efforts have been invested in understanding and designing chemical systems that can convert solar radiation into electrical energy. Organic, inorganic, and hybrid solar cells have garnered attention, with a particular focus on organic solar cells due to their higher efficiency.[16] These cells operate on the principle of absorbing photonic energy from solar radiation, leading to the creation of excited states that generate electronic current. Developing materials and polymers capable of efficiently transforming light into electricity remains a critical challenge and is pivotal to the success of this approach.

Proton Exchange Membrane (PEM) fuel cells utilizing hydrogen and oxygen gases offer another potential solution to meet the rising energy demand.. PEM fuel cells have attracted considerable research interest, particularly in the past decade, with the development of increasingly efficient catalysts, including nanoparticles and hydrogenase enzymes. One important consideration in this approach is the safe handling of hydrogen gas, which is highly flammable and explosive.



7. Renewable materials

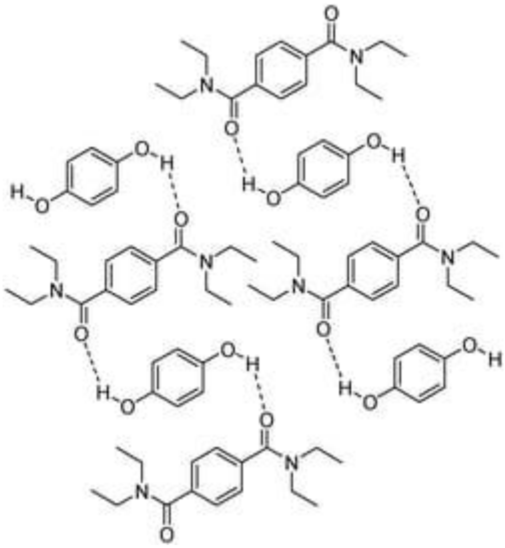
The majority of our manufacturing products have long been reliant on petroleum feedstock and natural gas. The depletion of these resources has far-reaching implications for both consumer life and the economy. Therefore, the shift towards renewable feedstocks, for both materials and fuels, has become an increasingly pressing concern. Biomass, the material derived from living organisms, stands out as the primary and abundant source of renewable feedstock on our planet. This includes a range of resources like wood, crops, agricultural residues, and food.[29]

Renewable materials obtained from biomass encompass cellulose, lignin, suberin, and various wood compounds, along with polyhydroxyalkanoates, lactic acid, chitin, starch, glycerol, and oil. Lignin, for example, has historically been a major waste product in the pulp and paper industry, often used for on-site energy production. However, in recent years, it has found new applications as dispersants, additives, and raw materials for the production of chemicals like vanilin, DMSO, or humic acid. Chitin, an abundant natural polymer found in the exoskeletons of arthropods (e.g., crustaceans), is another significant byproduct of the seafood industry. Through deacetylation, it can be transformed into chitosan. Chitosan has a multitude of applications, from water purification to biomedical uses and various industrial applications. Repurposing these waste products from the bio-industries holds the potential to provide a substantial supply of raw materials, reducing our reliance on current petroleum-based feedstocks.[17]

8. Derivates

Covalent derivatization is a widely used technique in chemistry, applied in both organic synthesis and analytical chemistry. However, in the early 1990s, an innovative concept called non-covalent derivatization emerged as a novel approach that does not rely on covalent bonding but rather on intermolecular interactions. This concept, developed by Warner, aimed to achieve chemical modifications with minimal energy and material consumption compared to traditional methods.

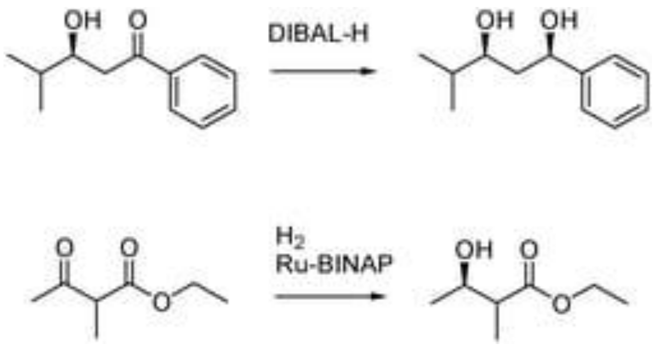
A prime example of non-covalent derivatization is illustrated in the controlled diffusion and solubility of hydroquinones used in Polaroid films. Researchers at Polaroid faced the challenge of releasing hydroquinones under elevated pH conditions. Instead of using conventional base-labile covalent protecting groups, they devised a non-covalent protecting group in the form of a co-crystal between hydroquinones and bis- (N, N-dialkyl) terephthalamides. This innovative approach proved successful and feasible for industrial processes. It effectively addressed the issue without modifying the original hydroquinone structures while minimizing waste material and energy consumption.[18]



9. Catalysis

In many instances, the generation of waste is closely associated with the traditional approach of using stoichiometric quantities of reagents. To enhance the efficiency of the synthetic toolbox, a significant shift from stoichiometric methods to catalytic processes is recognized as a key strategy. Catalysis plays a crucial role in improving reaction efficiency by reducing the energy input required, eliminating the need for stoichiometric reagents, and enhancing product selectivity.[19] This shift translates to reduced energy consumption, decreased reliance on feedstock, and minimized waste production. Furthermore, it often fosters the development of innovative chemical reactions and provides unconventional solutions to conventional chemical challenges.

This concept is well-illustrated in oxidation and reduction reactions. Reduction processes, which involve the use of DIBAL-H as a hydride donor, have long been a staple in organic chemistry. However, they tend to generate a significant amount of waste due to the necessity of stoichiometric reagents. Transitioning to catalytic hydrogenation methods like the Noyori hydrogenation effectively eliminates the need for stoichiometric reagents, resulting in reduced feedstock consumption and waste generation.

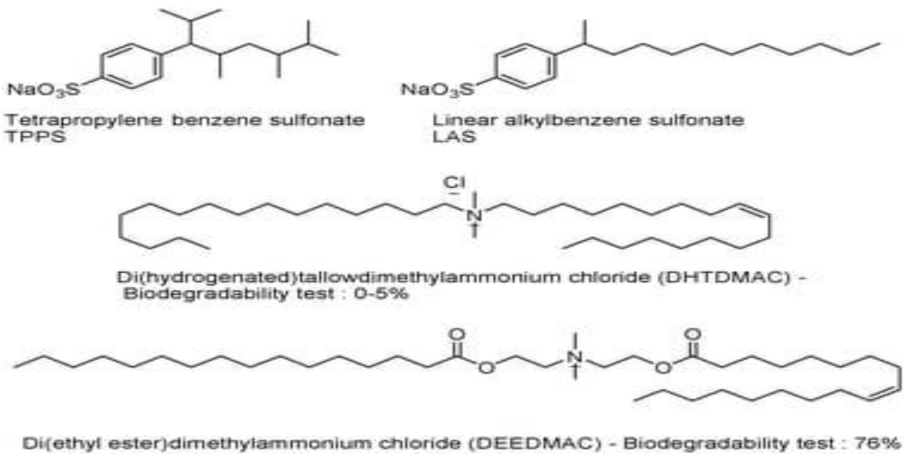


Catalysis extends its impact beyond mere efficiency; it enables the realization of reactions that might otherwise be unfavorable. An illustrative case is the metathesis reaction and the development of the Grubbs catalyst,[20] The introduction of a metathesis catalyst revolutionized the creation of unsaturated compounds, bringing about substantial environmental benefits and marked innovation.

Biocatalysis represents another exemplar of "green" chemistry, adopting a biomimetic approach that relies on natural or engineered enzymes. This concept encompasses both the direct use of purified enzymes and transformations facilitated by genetically modified living organisms. The reaction conditions in biocatalysis are typically mild, allowing transformations to occur in water at atmospheric pressure and ambient temperature. Moreover, enzymes exhibit superior levels of chemo-, regio-, and stereoselectivity.[21]

10. Biodegradation

The issue of persistence has been a long-standing concern, dating back to the early days of industrial development. This problem became notably evident in the 1950s when tetrapropylene alkylbenzene sulfonate (TPPS) was utilized as a surfactant in laundry detergents. Unfortunately, TPPS proved to be problematic as it didn't fully degrade and accumulated in the water supply. The severity of this situation was such that there were instances where "water would tend to foam when coming out of the tap." This prompted public outcry and pushed the industry to find an urgent solution.[21] Subsequently, it was discovered that replacing the methyl-branched chain of TPPS with a linear carbon chain could reduce its biopersistence. A common example of this substitution is the replacement of TPPS with linear alkylbenzene sulfonate (LAS).



Designing environmentally friendly and biodegradable materials and chemicals is a complex challenge, as evidenced by ongoing issues with environmental pollution. Over the years, certain patterns have emerged through extensive data collection. Chemical structures containing elements like halogens, branched chains, quaternary carbons, tertiary amines, and specific heterocycles tend to exhibit greater persistence and are generally avoided in design. Conversely, incorporating functional groups such as esters or amides, which can be recognized and processed by common enzymes, can aid in creating products that are environmentally degradable.

An example of this strategy can be seen in the development of surface-active quaternary ammonium compounds used in household fabric softeners. Prior to the 1990s, long-chain ammonium salts like di(hydrogenated)tallow dimethyl ammonium chloride (DHTDMAC) were being released into the environment. However, it was found that these compounds had a low rate of biodegradation in aquatic sediments and posed a significant ecotoxicity risk. In response, hydrolyzable amide or ester linkages were introduced in their design. These new ammonium salts proved to be more biodegradable, as illustrated in Figure 10. DHTDMAC was replaced by di(ethyl-ester) dimethyl ammonium chloride (DEEDMAC), resulting in a 70% increase in biodegradability.[22]

11. Analysis

The aim of green analytical chemistry is to measure chemicals without producing waste. Environmental concerns in analytical chemistry are typically associated with the analytical methods themselves. Many methodologies still require sample pre-treatment or rely on what can be termed "ex situ analysis," which is not always real-time direct analysis.

Process analytical chemistry is about monitoring a transformation in real-time and taking immediate action to prevent undesirable outcomes, but this is not always possible, and waste may be generated during the analysis. It's crucial for green chemists to consider the environmental impact of chosen analytical methods to avoid worsening environmental issues.

Green analytical chemistry involves using analytical procedures that minimize waste generation and pose fewer risks to human health and the environment. This definition encompasses both "live" monitoring of chemical processes and addressing the environmental drawbacks of traditional analysis. In-situ monitoring of reactions offers substantial advantages in terms of Green Chemistry. Acting swiftly can prevent accidents, save energy, and reduce the production of by-products that would require additional purification.

Analytical methods face two primary challenges in terms of environmental impact: the pretreatment of samples, including extraction, separation, or chemical modification, and the acquisition of signals. The use of solvents during sample pretreatment, which often involves large volumes of solvents, has been a major concern for analytical chemists. If solvent use is unavoidable for extraction, using eco-friendly alternatives like Accelerated Solvent Extraction (ASE) or supercritical fluid (SCF) extraction should be considered.[23]

Furthermore, the materials used in manufacturing analytical equipment should be selected with environmental considerations in mind. Both green chemists and green engineers developing new sensors should be aware of the toxicity and potential environmental issues associated with the materials they use. For instance, carbon-based electrodes like nanotubes or nanofibers are preferable replacements for mercury electrodes often used in electrochemistry.

12. Accident Prevention

The presence of dangerous substances and processes in our workplaces has increased over time. To prevent accidents, the initial step, as outlined in the "Chemical accident prevention and the clean air act amendments of 1990," involves identifying and evaluating hazards. These hazards encompass various aspects, including toxicity, physical threats like explosiveness or flammability, as well as broader environmental risks. It is imperative to consider these factors when designing chemicals and processes to avert incidents akin to those seen in Bhopal or the Love Canal incident.

A more recent and alarming example of these dangers can be observed in the unfortunate incident at UCLA in January 2009.[24] The mishandling of the commonly used but highly flammable butyllithium reagent tragically led to the death of a research assistant. This incident serves as a stark reminder to the scientific community that many chemicals still in use pose significant dangers and should, wherever feasible, be substituted with safer alternatives to prevent accidents.

❖ Green Chemistry in Education

Education stands as the foundational step in encouraging chemists to adopt more sustainable practices. Back in 1994, the idea of incorporating green chemistry into chemistry classes was initially suggested. However, it's worth noting that there is currently a limited availability of textbooks dedicated to green chemistry. The development of such textbooks holds significant potential for the education of graduates, postgraduates, teachers, and researchers.

Recognizing the importance of introducing green chemistry into both classrooms and laboratories, the Environmental Protection Agency (EPA) and the American Chemical Society have jointly initiated a substantial effort. They aim to create educational resources for green chemistry and to promote the integration of eco-friendly principles into the chemistry curriculum.

The successful adoption of environmentally friendly technology in academic and industrial settings relies heavily on students engaging with the principles and practices of green chemistry. Student Affiliate Chapters of the American Chemical Society can earn a "green" designation by actively participating in a minimum of three green chemistry activities during the academic year. Here are some suggestions for these activities:[25]

1. Hosting a guest speaker on the subject of green chemistry.
2. Organizing a campus workshop that explores multidisciplinary aspects of green chemistry.
3. Collaborating with a local business on a green chemistry initiative.
4. Creating green chemistry activities in partnership with nearby schools.
5. Adapting existing scientific experiments to be more environmentally friendly.
6. Planning a campus poster session dedicated to green chemistry.
7. Sharing a Green Chemistry Newsletter with the local community.
8. Developing an eco-friendly chemistry website.

These initiatives are geared toward fostering a culture of sustainability and environmental consciousness within the academic and research communities.[26]

INDUSTRIAL INTEREST IN GREEN CHEMISTRY

Numerous forward-thinking companies are increasingly adopting green chemistry practices, which not only benefit the environment but also enhance their financial performance and foster positive public relations.

It is estimated that U.S. businesses allocate an annual budget of $100 to $150 billion for compliance with environmental regulations. Furthermore, the substantial costs associated with cleaning up hazardous waste sites run into hundreds of billions of dollars. In many cases, the expenses incurred for adhering to environmental standards can surpass the funds allocated for research in various industries.[28] Large corporations, for instance, earmark approximately $1 billion each year for environmental compliance. By significantly reducing these compliance costs, companies can redirect the saved resources toward more profitable endeavors, thereby boosting their bottom line. Consequently, green chemistry, with its focus on pollution avoidance, offers advantages to both industry and the environment.

CONCLUSION

Green or Sustainable Chemistry refers to an approach focused on creating chemical products and processes that minimize or eliminate the use and generation of harmful substances. It exclusively employs chemicals and chemical processes that have no adverse environmental effects. This concept is built upon twelve guiding principles, which serve as a framework for designing molecules, materials, reactions, and processes that are safer for both human health and the environment.

Green Chemistry encompasses a wide spectrum of areas within the field, including organic, inorganic, biochemistry, polymer science, toxicology, environmental science, physical chemistry, and technology. Several prevailing trends in green chemistry, such as catalysis, biocatalysis, and the utilization of alternative and renewable resources like biomass, innovative reaction media like water and ionic liquids, modified reaction conditions such as microwave irradiation, and new synthetic pathways like photocatalytic reactions, contribute to achieving the dual objectives of safeguarding the environment and bolstering economic benefits.

This article provides examples of how Green Chemistry is making strides in minimizing the environmental impact of chemical processes and technologies.

REFERENCES

1. Ahluwalia, V.K. and Kidwai, M., New trends in green chemistry. Springer Science & Business Media, 2004.
2. Anastas, P. and Eghbali, N., Green chemistry: principles and practice. Chemical Society Reviews, 2010; 39(1): 301-312.
3. Anastas, P.T. and Williamson, T.C. eds., Green chemistry: designing chemistry for the environment. American Chemical Society, 1996.
4. Arends, I., Sheldon, R. and Hanefeld, U., Introduction: Green Chemistry and Catalysis. Green Chemistry and Catalysis, 2007; 1-49.
5. Behr, A., Vorholt, A.J., Ostrowski, K.A. and Seidensticker, T., Towards resource efficient chemistry: tandem reactions with renewables. Green Chemistry, 2014; 16(3): 982-1006.
6. Collins, T.J., The Green evolution. Letters to a Young Chemist. John Wiley and Sons, Hobocken, NJ, 2011; 77-93.
7. Csiba, M., Cleophax, J., Loupy, A., Malthete, J. and Gero, S.D., Liquid crystalline 5, 6-O-acetals of L-galactono-1, 4-lactone prepared by a microwave irradiation on montmorillonite. Tetrahedron letters, 1993; 34(11): 1787-1790.
8. Das, D., Pathak, G. and Rokhum, S.L., Polymer supported DMAP: an easily recyclable organocatalyst for highly atom-economical Henry reaction under solvent-free conditions. RSC advances, 2016; 6(106): 104154-104163.
9. Duvauchelle, V., Meffre, P. and Benfodda, Z., Green methodologies for the synthesis of 2-aminothiophene. Environmental Chemistry Letters, 2023; 21(1): 597-621.
10. Epsztein, R. and Le Goff, N., The preparation of conjugated trienediamines 1, 9-diaminonona-2, 7-diynes and their use in synthesis. Tetrahedron, 1985; 41(22): 5347-5352.
11. Fischmeister, C. and Doucet, H., Greener solvents for ruthenium and palladium-catalysed aromatic C–H bond functionalisation. Green chemistry, 2011; 13(4): 741-753.
12. Kerton, F.M. and Marriott, R., Alternative solvents for green chemistry (No. 20). Royal Society of chemistry, 2013.
13. Kidwai, M. and Mohan, R., Green chemistry: an innovative technology. Foundations of Chemistry, 2005; 7(3): 269-287.

14. Marziale, A.N., Jantke, D., Faul, S.H., Reiner, T., Herdtweck, E. and Eppinger, J. An efficient protocol for the palladium-catalysed Suzuki–Miyaura cross-coupling. Green chemistry, 2011; 13(1): 169-177.
15. Mestres, R., Green chemistry-views and strategies*(5 pp). Environmental Science and Pollution Research, 2005; 12: 128-132.
16. P. T. Anastas and J. C. Warner, in Green Chemistry: Theory and Practice, Oxford University Press, New York, 1998 Search PubMed ; I. Horvath and P. T. Anastas, Chem. Rev., 2007; 107: 2167.
17. Palmieri, A., Gabrielli, S., Cimarelli, C. and Ballini, R., Fast, mild, eco-friendly synthesis of polyfunctionalized pyrroles from β-nitroacrylates and β-enaminones. Green chemistry, 2011; 13(12): 3333-3336.
18. Park, K., FISHER SCIENCE EDUCATION.
19. Pochettino, A.A., Hapon, M.B., Biolatto, S.M., Madariaga, M.J., Jahn, G.A. and Konjuh, C.N., Effects of 2, 4-dichlorophenoxyacetic acid on the ventral prostate of rats during the peri-pubertal, pubertal and adult stage. Drug and Chemical Toxicology, 2016; 39(4): 392-399.
20. Samorì, C., Use of solvents and environmentally friendly materials for applications in Green Chemistry, 2010.
21. Schulz, W., ACS green chemistry initiatives get boost from EPA grant. Chemical & Engineering News, 1998; 76(33): 47-48.
22. Sodhi, G.S., Fundamental concepts of environmental chemistry. Alpha Science Int'l Ltd., 2005.
23. Trost, B.M. and Toste, F.D., Ruthenium-catalyzed cycloisomerizations of 1, 6-and 1, 7-enynes. Journal of the American Chemical Society, 2000; 122(4): 714-715.
24. Van Emelen, L., Henrion, M., Lemmens, R. and De Vos, D., C–N coupling reactions with arenes through C–H activation: the state-of-the-art versus the principles of green chemistry. Catalysis Science & Technology, 2022; 12(2): 360-389.
25. Wale, T., Suryavanshi, S., Wavare, V., Phalke, P. and Sharmale, M., Review on Green Chemistry. Journal of Drug Delivery and Therapeutics, 2023; 13(7): 190-193.
26. Wang, H., Gurau, G. and Rogers, R.D., Ionic liquid processing of cellulose. Chemical Society Reviews, 2012; 41(4): 1519-1537.
27. Wilkinson, S.L., Green Is Practical, Even Profitable. Chemical & engineering news, 1997; 75(31): 35-35.

28. Wolfs, J., Ribca, I., Meier, M.A. and Johansson, M., Polythionourethane thermoset synthesis via activation of elemental sulfur in an efficient multicomponent reaction approach. ACS Sustainable Chemistry & Engineering, 2023; 11(9): 3952-3962.
29. Zeng, T., Chen, W.W., Cirtiu, C.M., Moores, A., Song, G. and Li, C.J., Fe 3 O 4 nanoparticles: a robust and magnetically recoverable catalyst for three-component coupling of aldehyde, alkyne and amine. Green Chemistry, 2010; 12(4): 570-573.
30. Zeng, T., Chen, W.W., Cirtiu, C.M., Moores, A., Song, G. and Li, C.J., Fe 3 O 4 nanoparticles: a robust and magnetically recoverable catalyst for three-component coupling of aldehyde, alkyne and amine. Green Chemistry, 2010; 12(4): 570-573.