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REVIEW ARTICLE

GREEN CHEMISTRY: CHALLENGES AND OPPORTUNITIES IN SUSTAINABLE DEVELOPMENT

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ABSTRACT

The Green Chemistry revolution is providing an enormous number of challenges to those who practice chemistry in industry, education and research. With these challenges however, there are an equal number of opportunities to discover and apply new chemistry, to improve the economics of chemical manufacturing. Green chemistry is a philosophy and study of the design of products or substances that will not involve materials harmful to the environment. It is a modern science of chemistry that deals with the application of environmentally friendly chemical compounds in the various areas of our life such as industrial uses and many others. This area of chemistry had been developed by the need to avoid chemical hazards that organic and inorganic compounds had on the body of humans and animals. Chemistry plays a pivotal role in determining the quality of modern life. The chemicals industry and other related industries supply us with a huge variety of essential products, from plastics to pharmaceuticals. However, these industries have the potential to seriously damage our environment. Green chemistry therefore serves to promote the design and efficient use of environmentally benign chemicals and chemical processes. All these will be discussed in this article.

INTRODUCTION

Green Chemistry is defined as invention, design, development and application of chemical products and processes to reduce or to eliminate the use and generation of substances hazardous to human health and environment (Chandrasekaran *et al.*, 2009). The green chemistry revolution is providing an enormous number of challenges to those who practice chemistry in industry, education and research. With these challenges however, there are an equal number of opportunities to discover and apply new chemistry, to improve the economics of chemical manufacturing and to enhance the much-tarnished image of chemistry. Green chemistry is a philosophy and study of the design of products or substance.es that will not involve materials harmful to the environment. The ideal scenario is to virtually stop pollution before it can even begin through the use of non pollutants. Green chemistry is a relatively new area of chemistry that emerged by the need to reduce the hazardous effect of chemicals and to reduce the amount of environmental pollution that chemicals have. All these will be discussed in this article.

History of Green Chemistry

In 1990 the Pollution Prevention Act was passed in the United States. This act helped create a modus operandi for dealing with pollution in an original and innovative way. This paved the way to the green chemistry concept. Paul Anastas and John Warner coined the two letter word “green chemistry” and developed the twelve principles of green chemistry. In 2005 Ryoji Noyori identified three key developments in green chemistry: use of supercritical carbon dioxide as green solvent, aqueous hydrogen peroxide for clean oxidations and the use of hydrogen in asymmetric synthesis (Anastas and Warner, 1998).

Understand the origins of green chemistry

It is a modern science of chemistry that deals with the application of environmentally friendly chemical compounds in the various areas of our life such as industrial uses and many others. This area of chemistry had been developed by the need to avoid chemical hazards that organic and inorganic compounds had on the body of humans and animals. Most chemical compounds whether they are naturally made or are synthesized in the laboratory have negative effects on the human body although they are beneficial on a commercial basis. Especially notable are organic compounds which can easily penetrate the hydrophobic skin layer and enter the body. There it can exert an effect by binding to macromolecules in the body and alter their structure or interfere with their normal metabolism (Clark *et al.*, 1995).

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Concepts of Green Chemistry:

The concept of green chemistry incorporates a new approach to the synthesis, processing and application of chemical substances in such manner as to reduce threats to health and environment. This new approach is also known as:

- Environmentally benign chemistry
- Clean chemistry
- Atom economy
- Benign-by-design chemistry

Green Chemistry or environmentally benign chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances. Green chemistry was developed by virtue of the need to overcome this hazardous effect that toxic compounds exert on the body. This relatively new area of chemistry uses water as the medium of chemical reactions that are done in the laboratory. Chemical reactions are usually done in a medium that is called solvent. An exception is reactions that take place in the gas phase where there is no need for medium there. Sometimes chemical reactions are done in a neat fashion. Namely, the reacting compounds are mixed and reacted together with the need for a solvent. This is one of the methods that are used in green chemistry to avoid pollution and the hazardous effect of the volatile solvent. As a chemical philosophy, green chemistry applies to organic chemistry, inorganic chemistry, biochemistry, analytical chemistry and physical chemistry to minimize west, utilize renewable resources (Tundo and Anastas, 1999; James H. Clark, 1999; Tanaka and Toda, 2000; Ravichandran, 2010 and Clark, 1994).

Global Recognition of Green Chemistry

Australia: The Royal Australian Chemical Institute (RACI) presents Australia's Green Chemistry Challenge Awards;

Canada: The Canadian Green Chemistry Medal is an annual award given to any individual or group for promotion and development of green chemistry;

Italy: Green Chemistry activities in Italy centre on inter-university consortium known as INCA. In 1999, INCA has given three awards annually to industry for applications of green chemistry;

Japan: In Japan, The Green & Sustainable Chemistry Network (GSCN), formed in 1999, is an organization consisting of representatives from chemical manufacturers and researcher;

UK: In the United Kingdom, the Crystal Faraday Partnership, a non-profit group founded in 2001, awards businesses annually for incorporation of green chemistry;

USA: United States Environmental Protection Agency (EPA);

Nobel Prize: The Nobel Prize Committee recognized the importance of green chemistry in 2005 by awarding Yves Chauvin, Robert H. Grubbs, and Richard R. Schrock the Nobel Prize for Chemistry for "the development of the metathesis method in organic synthesis."

The challenges to chemists: Designing Safer Chemicals

Sustainable development is now accepted by governments, industry and the public as a necessary goal for achieving societal, economic and environmental objectives. Within this, chemistry has a key role to play in maintaining and improving our quality of life, the competitiveness of the chemical industry and the natural environment. This role for chemistry is not generally recognized by government or the public. In fact chemicals, chemistry and chemists are actually seen by many as causes of the problems. So chemists should be designed chemical products to preserve efficacy of the function while reducing toxicity. Chemists are molecular designers; they design new molecules and new materials. Green Chemists make sure that the things that we make not only do what they're supposed to do, but they do it safely (Tundo and Anastas, 1999; James H. Clark, 1999; Tanaka and F. Toda, 2000). This means that it's not only important *how* chemists make something, it's also important that *what* they make isn't harmful. In Chemistry: Function is NOT related to hazard. Making safe, non-toxic products is the goal.

Green Chemistry and Sustainable Development:

The UN defines sustainable development as 'meeting the needs of present without compromising the ability of future generation.' Green chemistry focuses on how to achieve sustainability through science and technology

- To better understand and solve the issue of environmental pollution, many approaches and models have been developed for environmental impact assessments.
- Some of these approaches and models have been successful in predicting impacts for selected chemicals in selected environmental settings.
- These models have joined air and water quality aspects to point and nonpoint sources and have been very useful for the development of emission control and compliance strategies.
- However, some of the approaches and models were aimed primarily at evaluating the quantity of pollutants that could be discharged into the environment with acceptable impact, but failed to focus on pollution prevention.

The concept of end-of-pipe approaches to waste management decreased, and strategies such as environmentally conscious manufacturing, eco efficient production or pollution prevention gained recognition.

The Twelve Principles of Green Chemistry

Green Chemistry is commonly presented as a set of twelve principles proposed by Anastas and Warner (1998). The principles comprise instructions for professional chemists to implement new chemical compound, and new synthesis and technological processes.

Prevention -It is better to prevent waste than to treat or clean up waste after it is formed;

Atom economy -Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product;

Less hazardous chemical syntheses -Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment;

Designing safer chemicals -Chemical products should be designed to preserve efficacy of function while reducing toxicity;

Safer Solvents and Auxiliaries -The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used;

Design for energy efficiency -The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used;

Use of renewable feedstock -Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure;

Reduce derivatives -A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable;

Catalysis -Reduce derivatives = Unnecessary derivatization (blocking group, protection/ de protection, temporary modification) should be avoided whenever possible. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents;

Design for degradation -Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products;

Real time analysis for pollution prevention -Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances and

Inherently safer chemistry for accident prevention - Substances and the form of a substance used in a chemical process should be chosen to minimize potential for chemical accidents, including releases, explosions, and fires.

Progress in Green Chemistry

Over the past decade, green chemistry has convincingly demonstrated how fundamental scientific methodologies can be devised and applied to protect human health and the environment in an economically beneficial manner. Significant progress has been made in key research areas, such as atom economy, alternative synthetic route for feed stocks and starting materials, bio-catalysis, green solvent, biosorption, designing safer chemicals, energy and waste management.

Atom Economy (Synthesis of Ibuprofen)

Atom economy is one of the fundamental principles of green chemistry. Atom economy looks at the number of atoms in the reactants that end up in the final product and by- product or waste.
% Atom economy = 100 x (FW of product /FW of reactants)

Alternative Synthetic Route for Feedstock & Starting Materials

Production of dimethylcarbonate (DMC) production DMC is a versatile and environmentally innocuous material for the chemical industry. Owing to its high oxygen content and blending properties, it is used as a component of fuel. Traditional method for the production of DMC This method involves the use of phosgene (COCl2) and methanol (CH3OH) as shown below:

COCl2 + 2CH3OH →CH3OCOOCH3 (DMC) + 2HCl

Alternative route for the production of DMC

This involves the use of copper chloride (CuCl), methanol (CH_3OH), oxygen (O_2) and carbon monoxide.

$2CuCl + 2CH_3OH + 1/2O2 \rightarrow 2Cu(OCH_3)Cl + H_2O$

$2Cu(OCH_3)Cl + CO \rightarrow 2CuCl + CH_3OCOOCH_3$

Bio-catalysis

Bioleaching is the extraction of specific metals from their ores through the use of microorganisms such as bacteria. This is much cleaner than the traditional heap leaching using cyanide in the case of gold extraction.

Extraction of gold

This can involve numerous ferrous and sulphur oxidizing bacteria, such as Acidithiobacillus ferrooxidans and Acidithiobacillus thiooxidans (also referred to as Thiobacillus). For example, bacteria catalyse the breakdown of the mineral arsenopyrite (FeAsS) by oxidising the sulphur and metal (in this case arsenic ions) to higher oxidation states whilst reducing dioxygen by H2 and Fe3+. This allows the soluble products to dissolve.

$FeAsS(s) \rightarrow Fe^{2+}(aq) + As^{3+}(aq) + S^{6+}(aq)$

This process occurs at the cell membrane of the bacteria. The electrons pass into the cells and are used in biochemical processes to produce energy for the bacteria to reduce oxygen molecules to water. In stage 2, bacteria oxidise Fe^{2+} to Fe^{3+} (whilst reducing O2).

$Fe^{2+} \rightarrow Fe^{3+} + e^-$

They then oxidise the metal to a higher positive oxidation state. With the electrons gained, they reduce Fe^{3+} to Fe^{2+} to continue the cycle. The gold is now separated from the ore and in solution.

Green Solvent

One of the green solvents is supercritical carbon dioxide ($scCO_2$). Supercritical carbon dioxide refers to carbon dioxide that is in a fluid state while also being at or above both its critical temperature and pressure (Tc = 31.3 oC, Pc = 1071 psi (72.9 atm) yielding rather uncommon properties. Supercritical carbon dioxide has been used as a processing solvent in polymer applications such as polymer modification, formation of polymer composites, polymer blending, microcellular foaming, particle production, and polymerization (Sheldon, 2005).

Reaction of amines with CO_2

$RNH_2 + CO_2 \longrightarrow RNHCOOH\ RNH_3 + RNHCOO^-$
$RNH_2 + 2H_2C\ (O)CH2 \longrightarrow RN(CH_2CH2OH)_2$
$H_2\ C\text{-}O\text{-}CH_2 + CO^{2-} \longrightarrow$ [COO-CR-C-O-] (polycarbonates)

Bio sorption

Bio sorption is one such important phenomenon, which is based on one of the twelve principles of Green Chemistry, i.e., "Use of renewable resources." It has gathered a great deal of attention in recent years due to a rise in environmental awareness and the consequent severity of legislation regarding the removal of toxic metal ions from wastewaters. In recent years, a number of agricultural materials such as the following have been used to remove toxic metals from wastewater:

Energy

Fossil fuel is dogged with many environmental pollution problems. There is, therefore, a growing need for alternative energy sources to replace fossil fuels. Renewable energy resources that are currently receiving attention include, solar energy, wind energy, hydro energy (Anastas and Williamson, 1998). Environmentally benign petrol can be obtained by the removal of Pb from petrol; by addition of ethanol produced from biomaterials to the petrol pool; by addition of methyl t-butyl ether (MTBE) to the petrol pool. MTBE has high octane and by use of electric vehicles powered by fuel cells.

Conclusion

The challenges in resource and environmental sustainability require more efficient and benign scientific technologies for chemical processes and manufacture of products. Green chemistry addresses such challenges by opening a wide and multifaceted research scope thus allowing the invention of novel reactions that can maximize the desired products and minimize the waste and byproducts, as well as the design of new synthetic schemes that are inherently, environmentally, and ecologically benign. Therefore, combining the principles of the sustainability concept as broadly promoted by the green chemistry principles with established cost and performance standards will be the continual endeavor for economies for the chemical industry. It is, therefore, essential to direct research and development efforts towards a goal that will constitute a powerful tool for fostering sustainable innovation. Green chemistry alone cannot solve the pressing environmental concerns and impacts to our modern era, but applying the twelve principles of green chemistry into practice will eventually help to pave the way to a world where the grass is greener.

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