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Green chemistry and sustainable development

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Abstract

Chemistry is truly very helpful to us as its applications are used globally for numerous purposes. Almost all products have been manufactured involving one or more chemical processes. Therefore, we cannot imagine our life without the products produced by the chemical industry. However, to obtain our desired products, always a large amount of wastes and hazardous materials are generated.

"Green Chemistry" is the universally accepted term which describes the movement towards more environmentally acceptable chemical processes and products. It was established about two decades ago and has attracted much attention. It reflects the efforts of academia and industry to address the challenges related to sustainable development of the chemical industry, and continuous progress is being made, both in academia and industry. Briefly, green chemistry is the utilization of a set of principles to reduce or eliminate the use or generation of hazardous substances in the design, manufacture and applications of chemical products. It is a tool in achieving sustainability, not a solution to all environmental problems. The slogan "benign by design" summarizes the ethos of green chemistry, and 12 principles guide its implementation.

Keywords: Green chemistry, Principles, Designing safer syntheses, Applications, Sustainable development.

1. Introduction

It is well known that the materials (clothes, grocery, foods, etc.) which are used by everyone daily are the product of modern chemistry. But with mass production of desired products comes mass waste. Due to the dumping of hazardous wastes into the environment without proper measures, air, water, food and ultimately human beings are highly affected.

The term "Green Chemistry" was introduced by Paul T. Anastas in 1991.[1] According to Anastas "Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances". The word "design" is very important because it cannot be made by accident; it is a thoughtful effort, it is a report of individual meaning. To produce safer chemical products, more research is needed. It is very much helpful to convey focus to growing interest in developing more environmentally friendly chemical processes and products. "Green Chemistry" is the universally accepted term which describes the movement towards more environmentally acceptable chemical processes and products.[2] It was established about two decades ago and has attracted much attention.[3,4] Green chemistry is a multidisciplinary field which covers areas like raw materials, solvents, synthesis, catalysis, products and efficient processes. In short, green chemistry is the reduction or elimination of use or production of hazardous substances with the help of a bunch of principles in the design, construct and functions of chemical products.[5]

The aim of green chemistry is not only fabrication of safer and less hazardous products but also saving water and energy which ultimately leads to sustainable development. Chemists and scientists must begin from the design of products and methods that reduce or eliminate the use and production of hazardous substances. Green Chemistry endeavors to decrease or remove, hazardous effect of products and feedstocks for the environment through design and changing the terms of manufacturing procedure. Green Chemistry has to cover a broad section of chemical and technological aspects in order to offer its alternative vision for sustainable development. Sustainable development means many things to many people and the range of actions and their implications is as varied. The attainment of sustainable development will require action by the international community, national governments, commercial and non-commercial organizations, plus individual action by citizens.

2. Green chemistry and sustainable development

"Green chemistry" and "sustainability" are new paradigm that assures to have a profound and long-term impact on the science of chemistry. Green chemistry and sustainability fundamentally go hand in hand. Sustainable development is gathering the requirements of the present generation without compromising the ability of future generations to meet their own needs. We want greener chemistry which efficiently uses renewable raw materials, removes waste and keep away from the use of toxic and or hazardous solvents and reagents in both products and process. Green chemistry is classified into two main components. First, it deals with the difficulty of efficient consumption of raw materials and the associated removal of waste. Second, it deals with the safety, health and environmental issues linked with the production, utilization and disposal or recycle of chemicals. Green chemistry is one of the most essential and powerful tools to use on the path to sustainability. In fact, without green chemistry and green engineering, there is no path to sustainability. The 12 principles of Green chemistry and their functions to basic and practical research are shortly illustrated below:

2.1. The 12 Principles of Green Chemistry

The most significant aims of Green Chemistry are described in twelve principles. Paul T. Anastas, an organic chemist working in the Office of Pollution Prevention and Toxins at the EPA, and John C. Warner developed the Twelve Principles of Green Chemistry in 1991.

2.1.1. Prevention

It is better to avoid waste than to treat or clean up waste after it has been formed. The ability of chemists to redesign chemical transformations to minimize the regeneration of hazardous waste is an important first step in pollution prevention. We have well known that “prevention is better than cure”. So it is better to prevent waste than clean it up after the fact.[6]

2.1.2. Atom Economy

Atom economy is a concept developed in the early 1990s to evaluate the efficacy of chemical conversions on element-by-element basis.[7] Synthetic routes should be planned to maximize the inclusion of all materials used in the process into the final product. This principle indicates that it is best to use all the atoms in a process and those atoms that are not used end up as waste. This concept is nowadays widely implemented in new routes to generate various organic compounds, e.g., such substances that are used in the biomedical and pharmaceutical field.[8,9,10]

2.1.3. Less Hazardous Chemical Syntheses

The target is to reduce the hazard of the chemicals which are utilized to generate a product. Selection of compounds and materials to be used to increase the efficacy of chemical transformations is a key point in process development; chemists should dedicate increased attention to the decision on which materials to be put into reaction vessels. So, less hazardous reagents and chemicals should be used in a process to make products.[11] Wherever feasible, synthetic processes should be designed to use and produce materials that have small or no toxicity to human health and the environment. Sometimes, chemists actually produce hazardous molecules, and, therefore, the subsequent principle is dedicated to the design of molecules which are intrinsically safer in their nature.[12]

2.1.4. Designing Safer Chemicals

Everybody desires safe products. This principle is aimed at designing products that are safe and non-toxic. Pharmaceuticals products often consists of chiral molecules and the difference between the two forms can be a matter of life and death. For example, when racemic Thalidomide (Figure 1) was administrated during pregnancy, leads to new born babies having terrible birth defects. Evidence indicates that only one of the enantiomers has the curing effect while the other isomer is the cause of severe defects.[13]

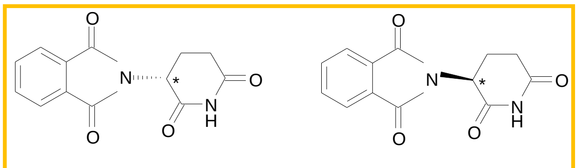

Figure 1. Structure of Thalidomide

2.1.5. Safer Solvents

Solvents are used regularly in our daily lives for various purposes like nail polish, cosmetics, cleaning products, etc and also in the chemistry laboratory. Many chemical reactions are done in a solvent. But the organic solvents have toxic effects and they can cause hazards. Solvents are extensively used in most of the syntheses.[14] Various solvents like toxic and volatile alcohol, benzene (carcinogenic), CCl_4, $CHCl_3$, perchloroethylene and CH_2Cl_2 are widely used for the syntheses. Large amount of solvents are also utilized for Purification (e.g. Chromatography) which causes pollution and highly hazardous to human health. The role of a solvent is very important for the development of green synthesis. So an ideal green solvent should be natural, nontoxic, nonflammability, nonmutagenicity, nonvolatility, cheap and readily available, easy to handle and recycle.[15,16] This principle concentrates on making products in such a way that they apply less hazardous solvents. It is obvious that water is the most inexpensive and environmentally benign solvent. According to the suitability of use, conventional solvents are suitable, usable, and undesirable (Table 1).

Table 1. Solvent selection according to usability [17].

Suitable	Usable	Undesirable
Methnol	Cyclohexane	Pentane
Ethanol	Methylcyclohexane	Hexane
Propan-1-ol	Heptanes	Diisopropyl ether
Propan-2-ol	Isooctane	Dichloromethane
Butan-1-ol	t-butyl methyl ether	Chloroform
t-butanol	Acetonitrile	Benzene
Ethyl acetate	Tetrahydrofuran	Dimethyl acetate
Isopropyl acetate	Acetic acid	Carbon tetrachloride
Acetone	Xylene	Dimethoxyethane
Methyl ethyl ketone	Tolune	Pyridine

2.1.6. Design for Energy Efficiency

We use energy for transportation purposes and to provide electricity to our homes and businesses. Traditional methods for creating energy have been found to contribute to global environmental problems such as Global Warming and the energy used can also be a significant cost.[18] So, energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If feasible, synthetic procedures should be carried out at ambient pressure and temperature. Table 2 shows possible ways to improve energy efficiency in the chemical industry [19].

Table 2. Improving Energy Efficiency in the Chemical Industry

Maintenance and recovery	Good insulation and well-maintained equipment reduce heat and energy loses. Waste generated by chemical processes often has an energy value and can be converted into useful fuel for office heating and hot water production. In some cases, this heat can be shared with the local community.
Chemical reactions-choice and conditions	It is necessary to choose the reactions and catalysts that require lower temperatures. In order to minimize energy requirements, the principle of increasing energy efficiency advocates the process of synthesis at room temperature and atmospheric pressure, whereby the use of catalyst is of great use. Catalysts are developed so that the process can be run at lower temperatures and pressures (high temperatures and pressures require enough energy).
Combined Heat and Power (CHP)	Production plants often generate their own cogeneration (Combined Heat and Power or CHP), which involves simultaneous production of electrical and useful heat energy in a single process. It is more efficient because it eliminates the loss in transmission, and the excess heat released during the cogeneration process can be used on site for various purposes.

2.1.7. Use of Renewable Feedstocks

According to the principles of green chemistry, a raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.[20,21,22,23,24,25] Using renewable resources like microbial or plant biomass, which are embedded into nature's closed carbon cycle, represents a real option to prepare functional bioproducts in a sustainable way and to contribute to energetic transition.[26]

About 90-95% of the products we use in our everyday lives are made from petroleum. Peoples not only depend on petroleum for energy and transportation, but also for manufacturing products. This principle wants to move our dependence on petroleum and to create products from renewable materials. Biodiesel is one example of this where researchers are trying to find alternative fuels that can be used for transportation.[27] Another example is bio-based plastics. Polylactic acid (PLA) is one plastic that is being made from renewable feed stocks such as corn and potato waste. About 1 kg of PLA requires about 2.5 kg of corn.[28] Benzene used in the commercial synthesis of adipic acid which is required in the manufacture of nylon, plasticizers and lubricants, has been replaced to some extent by the renewable and non-toxic glucose and the reaction is carried out in water.

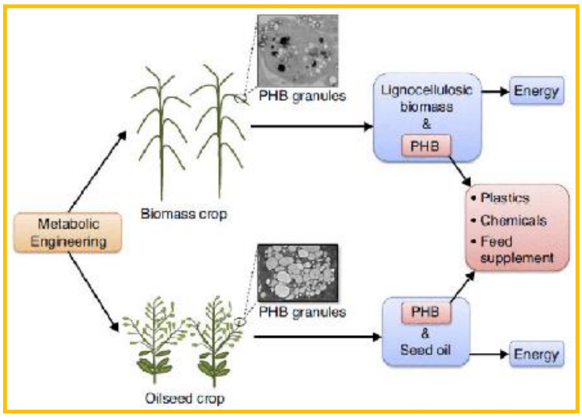

Figure 2. Schematic representation of the production of polyhydroxybutyrate (PHB) in both biomass and oilseed crops [29].

2.1.8. Reduce Derivatives

Unnecessary reactions for the formation of derivatives like protection/deprotection, use of blocking groups and temporary modification of physical/chemical processes etc. should be avoided or minimized if possible, because such steps require extra reagents and can produce more waste.[30] For many reactions that have traditionally required protecting groups, chemists are currently devoting research efforts to finding alternatives that do without them.[31] Typical example is the production of antibiotics (Figure 3) based on penicillin or replacement of classical chemical enzymatic processes whereby the 6-aminopenicillic acid is obtained by reacting with the catalyzed immobilized enzyme penicillin amide. This resulted in several chemical steps being replaced by an enzymatic reaction, and no longer required a low temperature (-60°C), organic solvents, and completely unsuitable conditions that increased and complicated production in the case of chemical synthesis.[32]

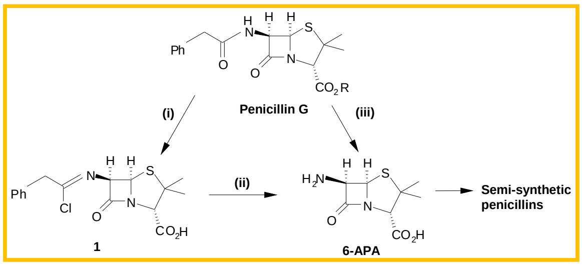

Figure 3. Synthesis of 6-aminopenicilic acid catalyzed by immobilized penicillin G amide [32].

2.1.9. Catalysis

Catalysis is the chemical reaction enabled or accelerated by a catalyst. According to Ostwald, catalysts are substances that speed up a reaction by enabling an energetically favored transition state between reactants (Figure 4), but which are not consumed by it and do not appear in the net reaction equation.[33] Catalysts play an important role in our modern industrial economy, in our stewardship of the environment, and in all biological processes. Saleh and others[34,35,36] reported that iron and copper sulfate as catalysts improved the mechanism of oxidative degradation of cellulosic wastes using 35% hydrogen peroxide.

In a chemical process catalysts are used in order to reduce energy requirements and to make reactions happen more efficiently.[37] It also reduces by-product formation. If the catalyst is truly a "green" catalyst it will have no toxicity in the process. Enzymes are wonderful examples of catalysts. Biocatalysed reactions are advantageous as they are performed in aqueous medium.

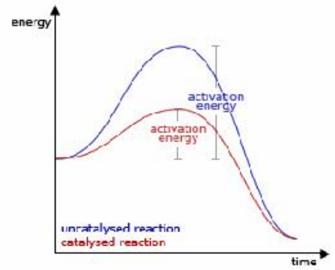

Figure 4. A plot of catalysed and uncatalysed reaction

The classic catechol synthesis is derived from benzene (non-renewable feedstocks) in several reaction stages requiring severe reactions under which undesirable byproducts are produced. It is replaced by a biocatalytic synthesis of D-glucose (renewable raw materials) in the presence of genetically modified Escherichia coli and is performed in one reaction stage (Figure 5), no byproducts and production is economically feasible.[38]

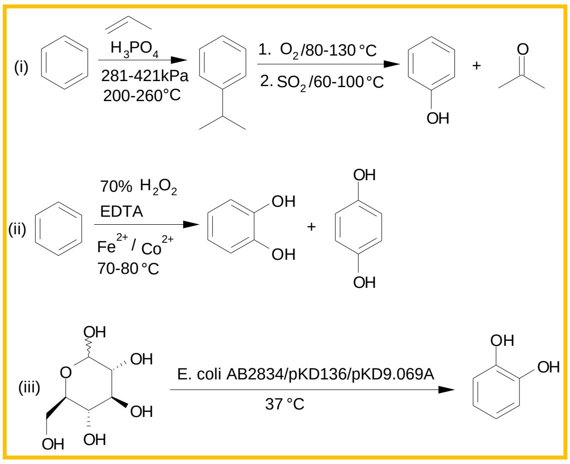

Figure 5. Catehole synthesis - classical (i), (ii) and biocatalytic (iii) [39].

In the context of catalysis, microwave-driven chemical reaction for organic chemistry is an emerging field to drastically reduce reaction times from days to only seconds. During the last decades, this technique has applied for industrial purpose.[40]

2.1.10. Design for Degradation

One of the most important objectives of green chemistry is maximizing the production with minimizing unwanted by-products. Designing of products and processes that display reduced impact on humans and the environment, such as creating sustainable mortar composite that could be considered as value-added product suitable for various applications as inert matrix for immobilization of some low and intermediate levels of radioactive wastes, decorative tiles, building bricks, and light concrete, is reported. In this case, highly reactive hydroxyl radicals react with the organic moieties of the spinning fiber wastes either by subtracting ions of hydrogen or by addition to the unsaturated site to yield organic radicals, which are readily oxidized by oxygen. Therefore, the end products of the degradation process were only carbon dioxide and water.[34,41,42,43]

2.1.11. Pollution Prevention

Everyone known that "prevention is better than cure". Pollution prevention is occurred using materials, process or practices that reduce or eliminate pollution or wastes at the source. With advancements in chemistry, the production of numerous toxic chemicals is a serious problem for the environment.[44] One of the basic concepts of green chemistry is familiar to pollution prevention practitioners. Less hazardous materials in chemical formulations and reducing waste formation have been sounded for many years. Consequently, green chemistry aims at eliminating the usage and generation of hazardous substances by designing better manufacturing processes for chemical materials with minimum waste production by real-time monitoring of running processes. This consequently enables a timely intervention right before waste or toxins are generated.[45]

2.1.12. Safer Chemistry for Accident Prevention

This principle focuses on safety for the worker and the surrounding community where an industry resides. It is better to use materials and chemicals that will not explode, fire, ignite in air, etc. when making a product. There are many examples where safe chemicals[46] were not used and the result was disaster. The most commonly known and perhaps one of the most shocking disaster was that of Bhopal, India in 1984 where a chemical plant had an accidental release that resulted in thousands of lives lost and many more injuries. When creating products, it is best to avoid highly reactive chemicals that have potential to result in accidents. When explosions and fires happen in industry, the result is often devastating.

For the production of gold nanoparticles, diborane (highly toxic and bursts into flame near room temperature) and benzene have been used. Nowadays, diborane has been replaced by environmentally benign $NaBH_4$ which also eliminates the use of benzene.[47] Nanoscience and nanotechnology is another important contribution to green chemistry.[48,49,50] Nanotechnology provides huge savings in materials by development of microscopic and submicroscopic electronic and mechanical devices.[51,52,53]

3. Teaching of Green Chemistry

Teaching must be in harmony with practice. The question of how to educate the future generation of chemists possessing the skill and knowledge to practice environmentally friendly chemistry lies in the centre of educational materials related to green chemistry.[54] Education is especially important in the popularization of green chemistry. Different international institutions, i.e. the American Chemical Society (ACS) and Polish Chemical Society (PTChem) are active in publishing materials that promote the rules and achievements of green chemistry. The green chemistry program should lead to sustainability by designing and using the methods in which natural raw materials will be economically processed, rational usage of energy sources, elimination of hazardous gaseous, liquid and solid wastes and by introduction of safety products for man. The popularization of green chemistry in school, among the workers at plants of chemical industry and distributors of chemical products is also very important.[55] The broad usage of green chemistry achievements will enable us to balance eco-development profitable for society, economy and the environment. The numerous educational materials, available currently on market[56] and on the Internet, are very helpful in everyday teaching of green chemistry principles.

4. Conclusion and future outlook

Green chemistry is not a new branch of science. It is a new philosophical approach through which sustainable development can achieved. Great efforts are still undertaken to design an ideal process that starts from nonpolluting materials. It is clear that the challenge for the future chemical industry is based on production of safer products and processes designed by utilizing new ideas in fundamental research. Furthermore, the success of green chemistry depends on the training and education of a new generation of chemists. Students at all levels have to be introduced to the practice of green chemistry. Scientists, engineers and industrialists should work together to promote the development of this field. There is no doubt that the development and implementation of green chemistry will contribute greatly to the sustainable development of our society.

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