Green chemistry education: a strategy for environmental control and sustainability

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Abstract. Green Chemistry is a subject that has attracted substantial prominence in recent years. This is due to its application in pollution control and maintenance of waste free environment. Green chemistry also known as sustainable chemistry, is the design of chemical products and processes that reduce or eliminate the use or generation of hazardous substances. This paper focused on the meaning of Green Chemistry, the 12 principles of Green chemistry, integration of the 12 principles of Green chemistry in the Secondary School Education Curriculum, benefits of Green Chemistry, strategies for encouraging Green Chemistry. The paper also highlighted the role of United States Environmental Protection Agency (EPA) and some of their partnering organizations across the globe.

Keywords: *green chemistry, education, secondary school education, pollution control.*

Introduction. Chemistry is a branch of science which tries to make people understand the nature, composition and usefulness of natural things and those made by human beings. Bajah, Teibo, Onwu and Obikwere (1992), observed that chemistry is not, like some people feel, a dangerous subject which deals with smelling chemicals. Chemistry enables anyone who studies it to learn certain useful scientific skills like separation of mixtures, mixing of substances proportionately, using specialized pieces of apparatus like burettes, pipettes and fractional distillation components. Chemistry has products and most of its products are man made. The process by which these chemistry products are created generates waste materials which are hazardous to the natural environment.

Green Chemistry. Green chemistry as a concept was coined by Paul Anastas in 1991. It is also called sustainable chemistry, it is a philosophy of chemical research and engineering that encourages the design of products and processes that minimize the use and generation of hazardous substances. Omiko (2013) observed that green chemistry is the chemistry that deals with the production and use of non-toxicants-materials. Green chemistry seeks to reduce and prevent pollution at its source.

Green chemistry according to the United States Environmental Protection Agency (EPA, 2013), applies across the life cycle of a chemical product, including its design, manufacture and use. As a philosophy, green chemistry applies to organic chemistry, inorganic chemistry, biochemistry, analytical chemistry and physical chemistry. It seems to focus on industrial applications, and which is aimed at minimizing the hazard and maximizing the efficiency of any chemical choice. It is different from environmental chemistry which is chemistry of the natural environment, and of pollutant chemicals in nature.

Developing and Integrating Green Chemistry Curriculum for Environmental Sustainability. Bajah et al (1992) observed that there are two substances in our physical environment which are of great importance to all living things. These two essential substances are Air and Water. Both air and water are essential for life. Okogun in Bajah et al (1992) opined that air and water constitute sources of raw materials for many chemical processes. Since green chemistry recognizes that there are significant consequences to the use of hazardous substances in our environment, it is important to integrate green chemistry-based curriculum into our secondary schools. This would enable the students at this level to learn how to use chemical products and processes to reduce or to eliminate the use and generation of hazardous substances in the society. Therefore in developing green chemistry-based curriculum, the 12 principles of green chemistry must be incorporated.

Principles of Green Chemistry. There are twelve Green chemistry principles. The principles were developed by two prominent chemists, Anastas and Warner (1998). These principles help in explaining what green chemistry means, the 12 principles cover such concepts as

(a) The design of processes to maximize the amount of raw materials that ends up in the product.

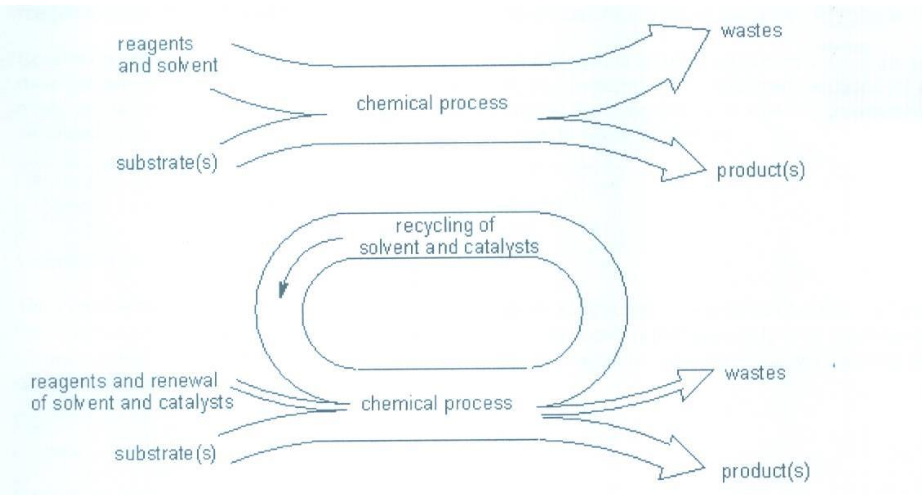
(b) The use of safe, environment-benign substances, including solvents, whenever possible;

(c) The design of energy efficient process.

(d) The best form of waste disposal: not to create it in the first place.

(e) The 12 green chemistry principles are:

1. **Waste prevention instead of remediation:** The ability of chemists to redesign chemical transformations to minimize the generation of hazardous waste is an important first step in pollution prevention. By preventing waste generation, we minimize hazards associated with waste storage, transportation and treatment.
2. **Maximize atom economy or efficiency:** Atom economy or efficiency is a concept developed by Barry Trost of Stanford University that evaluates the efficiency of a chemical transformation. Similar to a yield calculation, atom economy is a ratio of the total mass of atoms in the desired product to the total mass of atoms in the reactants. A typical chemical process generates products and solvents and reagents. However, if most of the reagents and solvent can be recycled, the mass flow looks quite different, examples; the two diagrams below illustrate waste management and recycling processes.



The prevention of waste can be achieved if most of the solvents are recyclable, for example, catalysts and reagents such as acids and bases that are bound to a solid phase can be filtered off, and can be regenerated (if needed) and reused in a subsequent run. In the production of chemical products on a large scale, heterogeneous catalysts and reagents can be kept stationary while the substrates are continuously added and pass through to yield a product that is continuously removed (for example by distillation).

Calculations involving Atom Economy or Efficiency

The mass efficiency of the above processes can be calculated by using environmental factor (E-Factor). E-Factor is defined by the following expression

E-factor = Mass of Wastes / Mass of Product

The ideal E factor of O(zero) is almost achieved in petroleum refining that needs constant removal of the product after each fractional distillation. The production of bulk and fine chemicals gives E factor of between 1 to 50.

Efficiency of Chemical Reactions

Another expression or formula used in calculating the efficiency of chemical reaction that is widely used is that of atom economy or efficiency. Here the value can be calculated from chemical equation of the reactants and products; example

Atom efficiency = Molecular weight of desired product / Molecular weight of all substances formed

Examples

(i) $FeSO_4.7H_2O_{(s)} \rightarrow FeSO_4.H2O_{(s)} + 6H_2\,O_{(g)}$

56+32+4(16)+2+16 6(18)

170 108

Where Fe = 56; S = 32; O = 16; H = 1

Atom efficiency for the above reaction = $\frac{170 \times 100\%}{170+108} = \frac{170 \times 100\%}{278}$

$= \frac{17000\%}{278} = 61.2\%$

(ii) $Fe_2O_{3(s)} + 3CO_{(g)} \rightarrow 2Fe + 3CO_{2(g)}$

2(56) + 3(12+2(16)

Atom efficiency = $\frac{2x56x100\%}{2x56+3(12+2(16))} = \frac{112x100\%}{112+3(12+32)}$

$= \frac{112x100\%}{112+36+96} = \frac{112x100\%}{112+36+96}$

$= \frac{11200\%}{244} = 45.9\%$

Atom efficiency is a highly theoretical value that does not incorporate any solvent, nor the actual chemical yield. One way to minimize waste is to design chemical transformations that maximize the incorporation of all materials used in the process into the final product, resulting in few if any wasted atoms. Choosing transformations that incorporate most of the starting materials into the product is more efficient and minimizes waste.

3. **Use of less hazardous and toxic chemical synthesis:** Whenever practicable, synthetic methodologies should be designed to use and generate substances that` possess little or no toxicity to human health and the environment. The goal is to use less hazardous reagents whenever possible and design processes that do not produce hazardous-by-products. This principle focuses on choosing reagents that pose the least risk and generate only benign-by-products.

4. **Designing safer chemicals:** Chemical products should be designed to affect their desired function while minimizing their toxicity. Toxicity and ecotoxicity are properties of the product. New products can be designed that are inherently safer, while highly effective for the target application. In the school laboratories, this principle should influence the design of synthetic targets and new products.

5. **Use safer solvents and auxiliaries:** The use of auxiliary substances (examples, solvents, separation agents, etc) should be made unnecessary whenever possible and innocuous when used. Solvents use leads to considerable waste. Reduction of solvent volume or complete elimination of the solvent is often possible. In cases where the solvent is needed, less hazardous replacements should be employed. Avoid purifications when possible and minimize the use of auxiliary substances when they are needed.

6. **Design for energy efficiency:** Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic and purification methods should be designed for ambient temperature and pressure, so that energy costs associated with extremes in temperature and pressure are minimized.

7. **Use only renewable feedstocks:** A raw material or feedstock should be renewable rather than depleting

whenever technically and economically practicable. Whenever possible, chemical production should be designed to utilize raw materials and feedstocks that are renewable, examples of renewable feedstocks include agricultural products or the wastes of other processes. Examples of depleting feedstocks include raw materials that are mined or generated from fossil fuels (petroleum, natural gas or coal).

8. **Avoid chemical derivatives:** Unnecessary derivation (use of blocking groups, protection/deprotecion, temporary modification of physical/chemical processes) should be avoided or minimized if possible, because such steps require additional reagents and can generate waste. Synthetic transformations that are more selective will eliminate or reduce the need for protecting groups. In addition, alternative synthetic sequences may eliminate the need to transform functional groups in the presence of other sensitive functionality.

9. **Use catalyst:** Catalytic reagents (as selective as possible) are superior to stoichiometric reagents. Catalysts can play active roles during a transformation process. They can enhance the selectivity of a reaction, reduce the temperature of a transformation, enhance the extent of conversion to products and reduce reagent-based waste because they are not consumed or affected during the reaction. However, by reducing the temperature, one can save energy and potentially avoid unwanted side reactions.

10. **Design for degradation:** Chemical products should be designed so that at the end of their function or use, they breakdown into innocuous degradation products and do not persist in thee environment. Efforts related to this principle focus on using molecular-level design to develop products that will degrade into hazardless substances when they are released into the environment.

11. **Real-time analysis for pollution prevention:** It is always important to monitor the progress of a reaction to know when the reaction is complete or to detect the emergence of any unwanted by-products. Whenever possible, analytical methodologies should be developed and used to allow for real-time, in-process monitoring and control to minimize the formation of hazardous substances.

12. **Inherently safer chemistry process for pollution and accident prevention:** One best way to minimize the potential for chemical accident and pollution is to choose reagents and solvents that minimize the potential for explosions, fire outbreaks and accidental release. Risks associated with these types of accidents can sometimes be reduced by altering the form (solid, liquid or gas) or composition of the reagents.

Benefits Derived from the Application of Green Chemistry

There are a lot of benefits derived from the application of green chemistry, such benefits include:

- The use and production of those chemicals or designs that may involve reduced waste products, non-toxic components, and improved efficiency.
- Green chemistry is the best approach to pollution innovative scientific solutions to real-world environmental situations. Materials/chemicals produced in green chemistry are those chemicals that are less hazardous to human health and the environment. They include:

(a) Chemicals/products that are less toxic to organisms

(b) Non-persistent (degradable) or bioaccumulative in organism or the environment in which they are produced.

(c) Inherently safer with respect to handling and use

- Green chemistry encourages the use of recycling processes in converting already used materials to new products. This process leads to wealth creation from wastes (it is known as from “waste to wealth”).
- According to the United States’ Environmental Protection Agency (EPA, 2013), Green Chemistry technologies provide benefits such as:

(a) It helps to reduce waste and eliminate costly end-of-the-pipe treatments.

(b) It leads to the production of safer products.

(c) The technologies involved in the green chemistry reduce the use of energy and resources.

(d) It improved competitiveness of chemical manufacturers and their customers.

- Green chemistry encourages the treatment of chemicals to render them less hazardous during use or application.
- The technologies involved in green chemistry incorporate designs that help in disposal of chemicals properly to prevent environmental pollution.

Strategies Involved in Encouraging Green Chemistry

The following Strategies should be used in encouraging the use and development of Green Chemistry

1. **Legislation in favour of green chemistry:** There should be laws against the use or production of substances that are toxic and harmful to human health and the environment. In 1990, the United States o America passed Pollution Prevention Act (PPA). This Act helped the American government to deal with pollution in an original and innovative way. In 2007, Europe put into place the registration, evaluation, authorization, and restriction of chemicals (REACH) program, which requires companies to provide data showing that their products are safe. This regulation ensures not only the assessment of the chemicals’ hazard as well as risks during their uses but also includes measures for banning or restricting/authorizing uses of specific substances.

2. **Giving award to green chemistry users:** The State and Federal Governments should collaborate with the industries to create an Agency or Commission that would be responsible for the selection and awards of prices to green chemistry performers. The awards should highlight successes in research, development, and industrial implementation of technologies that prevent pollution at the source while contributing to the competitiveness of the innovators.

3. **Giving of grants for green chemistry research:** The government and the captains of industries should provide fund for green chemistry research. Those scientists, or scholars who are interested in carrying out research in green chemistry should be encouraged by providing fund for the research.

4. **Educational activities on green chemistry:** The government can promote green chemistry through education by providing educational materials, such as books, equipment or instructional materials, production and distribution of green chemistry materials.

5. **Organizing conferences, seminars and workshops on issues relating to green chemistry:** Documentation

and creating awareness among the academia and the general public about green chemistry is very important. It is during conferences, seminars and workshops that new ideas or concepts are developed and shared by the participants. Issues relating to green chemistry, like, the 12 principles of green chemistry must be fully understood by the participants of the conference, seminars/ workshop.

6. **Establishing good relationship with the United States Environmental Protection Agency (EPA):** EPA's Green Chemistry Program works with many partners to promote pollution prevention through the application of green chemistry principles. Partnering organizations that work with EPA are many and they represent the academia, industry, government agencies, scientific societies, trade organizations, national laboratories, research centers, professional bodies among others. Presently, the following organizations are partnering with EPA in the invention, designing and application of chemical products and processes to reduce or eliminate the use and generation of hazardous substances.

(a) Education centres

(i) Center for sustainable Systems at the University of Michigan
(ii) Chemical Education Foundation
(iii) Partnership for Environmental Technology Education
(iv) Beyond benign, etc

(b) Academia

(i) Center for Green Chemistry and Green Engineering at Yale
(ii) The University of Alabama
(iii) University of Massachusetts Lowell
(iv) University of Nigeria, Nsukka, Nigeria
(v) University of Ibadan, Nigeria
(vi) University of Oregon
(vii) Greener Education Materials for Chemists, etc

(c) Scientific Organizations

(i) America Chemical Society (ACS)
(ii) Green Chemistry Institute (GCI)
(iii) Green Chemistry Education Resources
(iv) Council for Chemical Research (CCR)
(v) International Union of Pure and Applied Chemistry (IUPAC), Organic and Biomolecular Chemistry Division.
(vi) National Research Council (NRC) – Board on Chemical Sciences and Technology
(vii) Nigeria Research Council
(viii) National Science Foundation (NSF) – Chemistry and Materials
(ix) Society for Environmental Toxicology and Chemistry (SETAC)

(d) Trade Association

(i) American Chemistry Council
(ii) America Petroleum Institute (API)
(iii) Society of Plastics Industry (SPI)

(e) Industry

(i) Goodrich Corporation (Former BF Goodrich Company)
(ii) The Dow Chemical Company
(iii) Dow Corning Corporation
(iv) E.I. DuPont De Nemours
(v) Eastman Kodak Company
(vi) Polaroid Corporation
(vii) Rochester Midland Corporation

(f) Research centres

(i) Center for Process Analysis and Control (CPAC) at the University of Washington
(ii) Emission Reduction Research Center (ERRC) at the New Jersey Institute of Technology
(iii) National Environmental Technology Institute (NETI) at the University of Massachusetts Amherst.
(iv) Toxics use Reduction Institute (TURI) at the University of Massachusetts Lowell.

(g) Government

(i) Environmental Council of the States (ECDS)
(ii) Environmental Protection Agencies in Nigeria
(iii) National Institute of Standards and Technology (NIST)
(iv) U.S. Department of Energy (US, DOE), Office of Energy Efficiency and Renewable Energy.

(h) National Laboratories

(i) Los Alamos National Laboratory (LANL)
(ii) National Renewable Energy Laboratory (NREL)

(i) Environmental Groups:

There are many environmental groups across the globe; one example is the Environmental Defense (EDF) group.

(j) **International Organization**s

There are many International Organizations that are involved in green chemistry operation. Such organizations include:

- Canadian Green Chemistry network (CGCN) – Canada
- Centre for Green Chemistry (Australia)
- Crystal Faraday (now Chemistry Innovation KTN) Great Britain
- Green and Sustainable Chemistry Network (GSCN), English and Japan.
- International Union of Pure and Applied Chemistry (IUPAC)
- Inter-University Consortium: Chemistry for the Environment (Italy), among others.

Conclusion. The environment is where organisms including human beings are found. It is the total surrounding of living things. The environment is considered polluted when it is altered in composition or condition directly or indirectly as a result of the activities of man so that it becomes less suitable for some or all of the uses for which it would be suitable in its natural state. According to the World Health Organization (WHO), Cleanliness is next to godliness.

Green Chemistry also called sustainable chemistry is a philosophy of chemical research and engineering which encourages the design and use of products and processes that minimize the use and generation of hazardous substances. This philosophy applies to all the branches of chemistry (organic chemistry, inorganic chemistry, Biochemistry, analytical chemistry, physical chemistry and polymer chemistry). It aims at safer environment, reduced waste generation among others. Therefore, to achieve safe environment and the design of products and processes that reduce the use and generation of hazardous substances, every nation should encourage the application of the twelve (12) principles of green chemistry.

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