

for chemical accidents, including releases, explosions, and fires. Manufacture of gold atom nanoparticles used diborane (highly toxic and bursts into flame near room temperature) and cancer-causing benzene. Now, diborane has been replaced by environmentally benign sodium borohydride (NaBH_4), which also eliminates the use of benzene. Nanoscience and nanotechnology are another important contribution to green chemistry. Nanotechnology provides huge savings in materials by development of microscopic and submicroscopic electronic and mechanical devices.

Examples of Green Chemistry in Industry

Let us look into some common examples of Green chemistry in industries:

1. The most polluting reaction in industry is oxidation. Implementation of green chemistry has led to the use of alternative less polluting reagents, viz., metal ion contamination is minimized by using molecular O_2 as the primary oxidant and use of extremely high oxidation state transition metal complexes.
2. Diels–Alder reaction is 100% atom economy reaction as all the atoms of the reactants are incorporated in the cyclo-adduct. Other examples of reactions often exploited in industry are isomerization reaction, metathesis, and addition reactions, which are quite atom economical processes.
3. Conventional methylation reactions employing toxic alkyl halides or methylsulfate, leading to environmental hazard are replaced by dimethyl carbonate with no deposit of inorganic salts. For example, methylation of aryl acetonitrile in the presence of K_2CO_3 to 2-arylproponitriles (>99%).
4. The use of phosgene and methylene chloride in the synthesis of polycarbonates has been replaced by diphenyl carbonate.
5. Use of CO_2 as a reaction medium for asymmetric catalytic reductions, particularly hydrogenation and H_2 transfer reactions.
6. A convenient green synthesis of acetaldehyde is by *Wacker's oxidation* of ethylene with O_2 in the presence of a catalyst, in place of its synthesis by oxidation of ethanol or hydration of acetylene with H_2SO_4 .

Matrices to Express Greenness

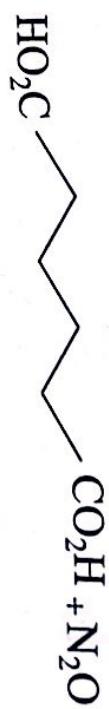
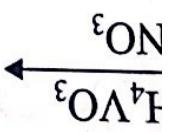
E-Factor

The greenness of a chemical process can be expressed by a term called E-Factor (environmental factor) which was introduced by Roger Sheldon. It is defined as the mass ratio of waste to desired product.

$$\text{E-Factor} = \frac{\text{Total mass of waste}}{\text{Product mass}}$$

[22.1]

Although the ideal E-factor of 0 is almost achieved in petroleum refining, the production of bulk and fine chemicals gives E-factors of between 1 and 50. Typical E-factors for the production of pharmaceuticals lie between 25 and 100. Note that water is not considered in this calculation, because this would lead to very high E-factors. However, inorganic and organic wastes that are diluted in the aqueous stream must be included. Sometimes it is easier to calculate the E-factor from a different viewpoint, since accounting for the losses and exact waste streams is difficult:

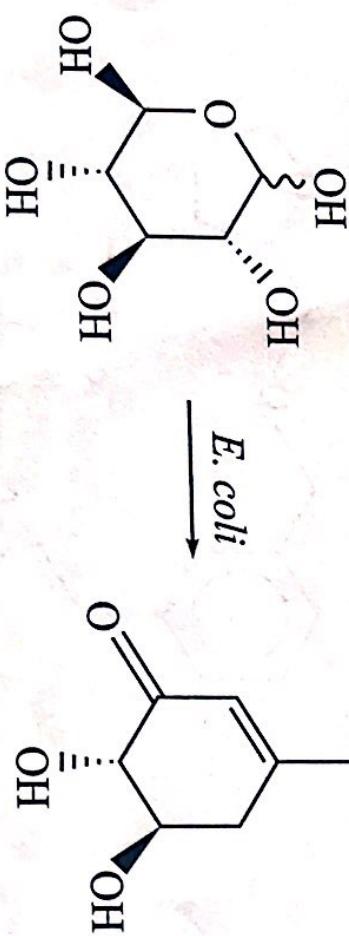


Adipic acid

Greener



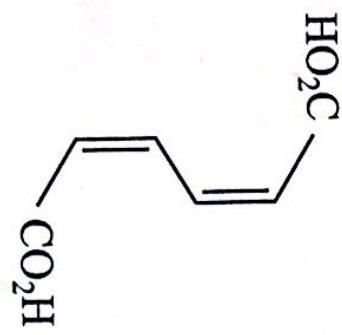
E. coli



D-glucose

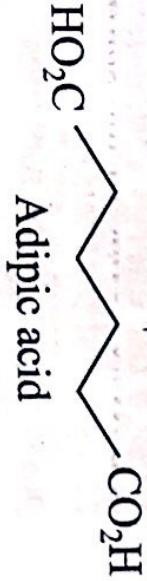
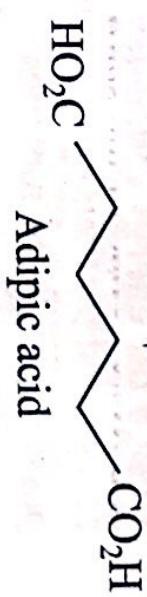
3-dehydroshikimate

E. coli



cis, cis-muconic acid

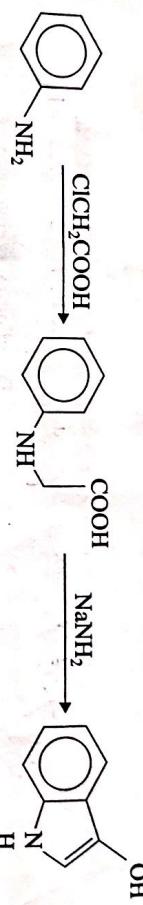
50psi



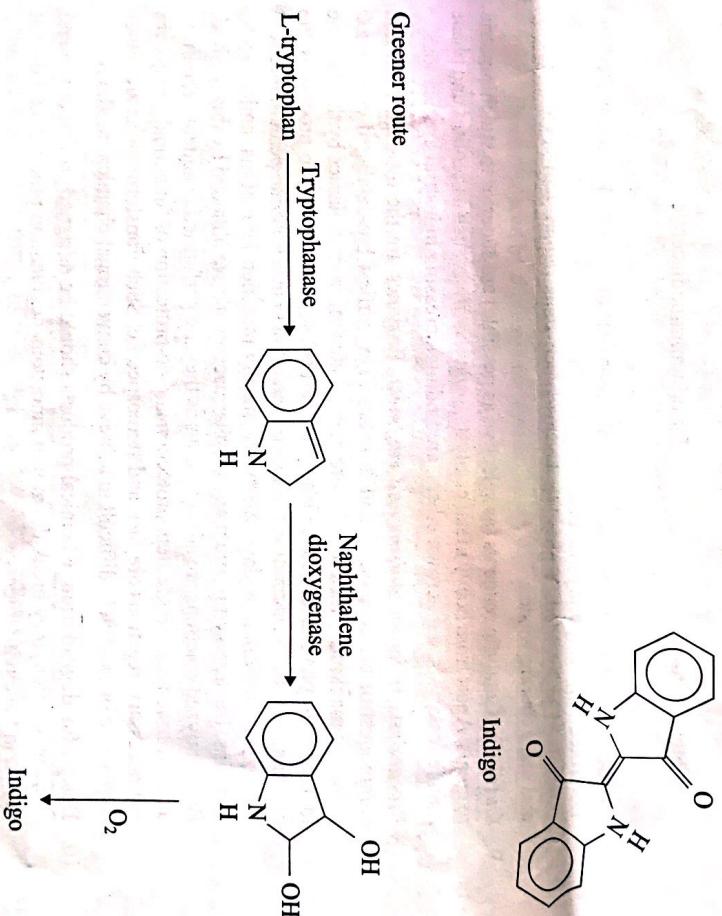
Adipic acid

Indigo is a widely used dye. This is prepared by taking aniline as the starting material, which is highly toxic. In addition, the conventional process also generates considerable amount of waste salts. In the greener method, it is made by removal of side chain of tryptophan to give indole which is then hydroxylated and then oxidized to yield indigo.

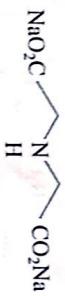
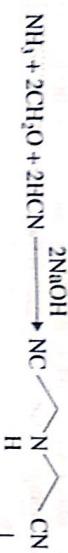
Conventional route



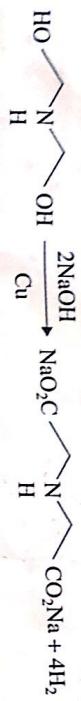
Greener route



The traditional method of synthesis of disodium iminodiacetate involves highly toxic KCN as one of the starting material. In greener approach, it is prepared from diethanolamine as the starting material.

Conventional route

Disodiumiminodiacetate

Greener route

Diethanolamine

Disodiumiminodiacetate

8. **Reduce derivatives:** Unnecessary derivatization (use of blocking groups, protection/de-protection, temporary modification of physical/chemical processes) should be minimized or avoided, if possible, because such steps require additional reagents and can generate waste.

9. **Catalysis:** Catalytic reagents (as selective as possible) are superior to stoichiometric reagents. Apart from heavy metal catalysts, *softer catalysts* such as zeolites and phase transfer catalysts, e.g., crown ethers, are finding increasing industrial applications.

- Biocatalysis (microorganisms and enzymes):** Enzymes are the most efficient and commonest of the catalysts found in nature. The earliest bio-catalyzed conversion known to mankind is the manufacture of ethyl alcohol from molasses by the enzyme invertase. In pharmaceutical industry, the largest scale bio-catalytic process is the conversion of the fermentation product of Penicillium G into 6-amino penicillanic acid by enzyme penicillin acylase. Many chemically modified Penicillins, amino acids, vitamins, fructose syrup, and many biopharmaceuticals are obtained by this method. Bio-catalyzed reactions are advantageous as they are performed in aqueous medium, all conversions are single step, protection and de-protection of functional groups are not necessary, reactions are fast, and stereospecific. Such transformations are either impossible or extremely difficult to achieve by conventional chemical methods.

10. **Design for degradation:** Chemical products should be designed so that at the end of their function, they break down into innocuous degradation products and do not persist in the environment.

11. **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.

12. **Inherently safer chemistry for accident prevention:** Substances and the form of a substance used in a chemical process should be chosen to minimize the potential

$$\text{E-Factor} = \frac{\text{Weight of raw materials} - \text{Weight of product}}{\text{Weight of product}}$$

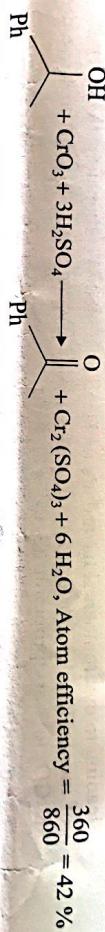
[22.2]

A higher E-factor means more waste, which leads to a greater negative environmental impact. Note that water is not considered in this calculation, because this would lead to very high E-factor value. However, inorganic and organic wastes that are diluted in the aqueous stream must be included.

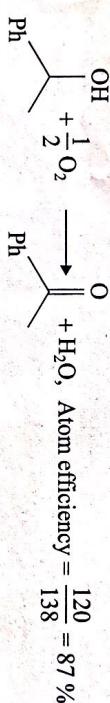
Atom Economy

The concept of atom economy or atom efficiency was first introduced by Barry Trost. This is an extremely useful tool for the evaluation of the amounts of waste that will be generated by different processes. It is the ratio of the molecular mass of the product and the total molecular mass of all substances formed as represented in the stoichiometric equation for the reaction. In contrast to the E-factor, it is a theoretical number based on stoichiometric amounts and disregards those substances which do not appear in the stoichiometric equation. For example, the atom efficiencies in oxidation of a secondary alcohol to the corresponding ketone are compared. In the first scheme, stoichiometric CrO_3 is used, whereas the second is carried out in the presence of a catalyst.

Scheme 1



Scheme 2



Environmental Quotient

The E-factor and atom economy can be used for comparing reaction alternatives, but we should remember that there are different types of wastes. The reaction described above has two by-products, i.e., chromium sulfate and water. Obviously, water is a good waste, while chromium sulfate is a bad waste. Therefore, evaluating synthetic processes on the basis of only the amount of waste produced is insufficient. To solve this problem, Sheldon put forward the concept of the environmental quotient (EQ). It is obtained by multiplying the E-factor by Q , an arbitrarily assigned hazard quotient. This measure takes into account both the amount and the nature of the waste. Assigning absolute Q -values to waste streams is difficult, because cases differ according to location and type of waste. Nevertheless, the EQ gives a better measure of the environmental impact of a process than the E-factor or the atom economy alone.

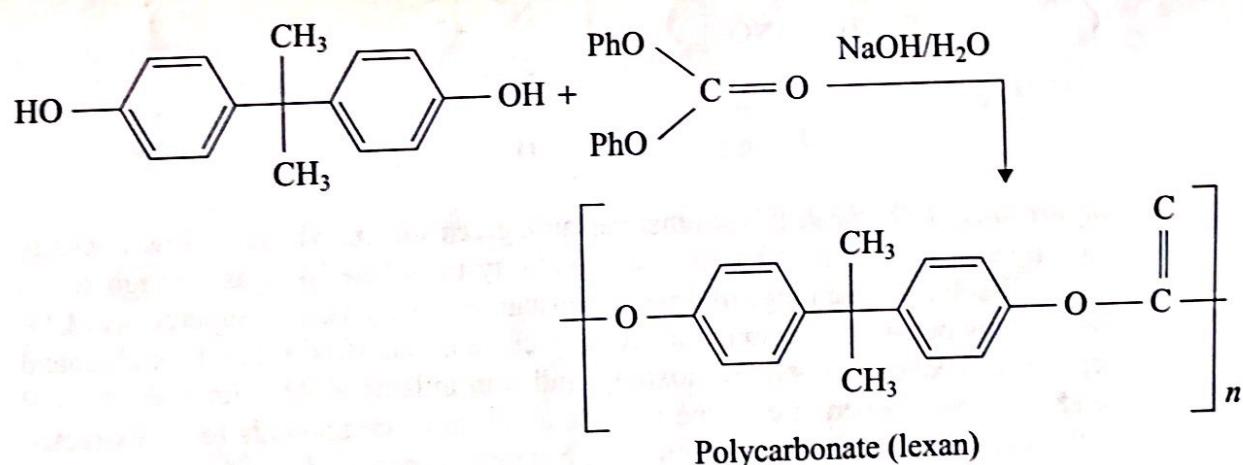
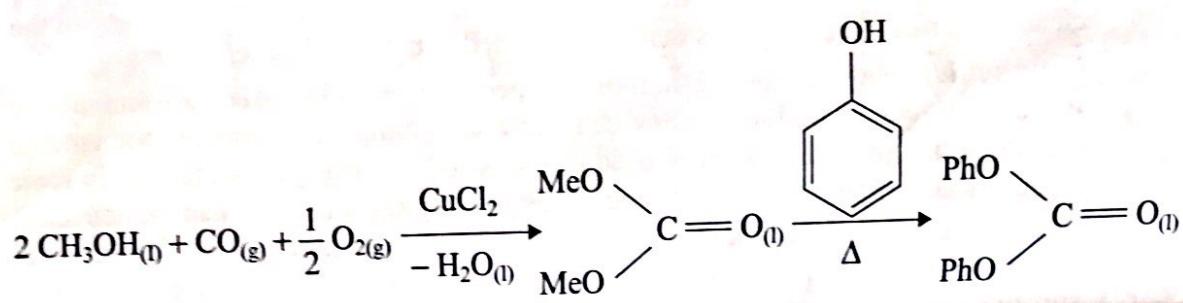
Green Chemistry and Catalysis

In the light of Green chemistry principles, a good catalyst possess the following qualities:

common one is manufactured from bisphenol A by condensation reaction with carbonyl chloride (phosgene). The reaction is a two-phase reaction (i.e., water + immiscible organic solvent). The Bu_4N^+ is a *phase transfer catalyst*, which improves the solubility of the phenolate in the organic phase and greatly speeds reaction. This is an example of an *interfacial polymerization*. Carbonyl chloride is a very poisonous gas, manufactured from other hazardous gases such as carbon monoxide and chlorine.

Greener method

Greener method
Polycarbonates can also be made by ester exchange using dimethyl carbonate or diphenyl carbonate. The process for the production of polycarbonate that uses dimethyl/diphenyl carbonate is less hazardous than the process of using phosgene or carbonyl chloride. Dimethyl carbonate is readily manufactured from methanol, carbon monoxide, and oxygen in the liquid phase, in the presence of copper (II) chloride, $CuCl_2$. Diphenyl carbonate is produced from dimethyl carbonate by heating with phenol in the liquid phase.



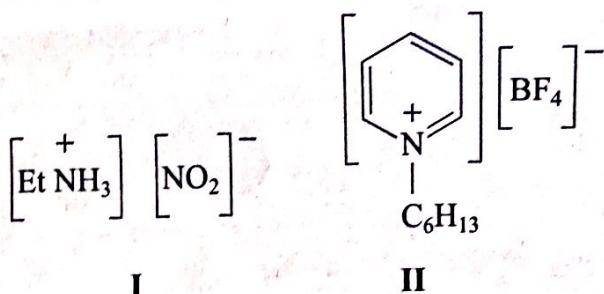
- (ii) In the manufacture of polystyrene foam sheet packing material, chlorofluorocarbons which contribute to O₃ depletion, global warming, and ground level smog have now been replaced by CO₂ as the blooming agent.

4. **Design of relatively safe chemicals:** Chemical products should be designed to cause their desired function keeping their toxicity at a minimum level. For example, racemic thalidomide (thalidomide marketed under the brand names InmunoPrin/

Talidex/Talizer/Thalomid is an immunomodulatory drug) when administered during pregnancy leads to horrible birth defects in many new born. Evidence indicates that only one of the enantiomers has the curing effect, while the other isomer is the cause of severe defects. This is why it is vital to produce the enantiomeric forms separately so that associated hazard can be reduced by maintaining their performance. Catalysts that can catalyze important reactions that produces only one of the two mirror image forms have been developed.

5. **Safer solvents and auxiliaries:** The use of auxiliary substances such as solvents and separating agents should be made unnecessary wherever possible and innocuous when used. Solvents such as alcohol, benzene (carcinogenic), CCl_4 , CHCl_3 , perchloroethylene, and CH_2Cl_2 are extensively used in most of the syntheses and most of them are toxic and volatile. Purification steps also utilize and generate large amounts of solvent and other wastes (e.g., chromatography supports). These have now been replaced by safer green solvents such as ionic liquids, supercritical CO_2 fluid, water or supercritical water, and also solvent-free systems that utilize the surfaces or interiors of clays, zeolites, silica, and alumina. These are the basis of many of the cleaner chemical technologies that have reached commercial development.

Ionic liquids: These are liquids at room temperature and below. They are nonvolatile and have no vapor pressure. They can serve as optimal replacements for volatile organic compounds traditionally used as industrial solvents. The reactions in ionic liquids need no special apparatus and methodologies, and they can be recycled. However, large-scale applications are still not known. The first ionic liquid I was discovered in 1914 and many binary ionic liquids of type II are also used as green solvents.

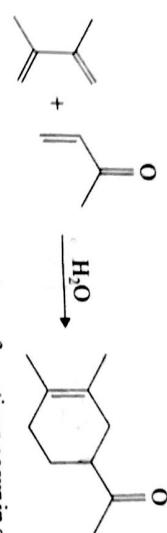


Supercritical CO_2 fluid: It is another versatile green solvent which has low viscosity and no surface tension. It has the unique ability to diffuse like gas through solids and to dissolve a wide range of organic substances, catalysts, etc. Supercritical CO_2 fluid is now becoming an important commercial and industrial solvent for chemical separation because of its low toxicity and non-inflammability. Its stability and relatively low temperature of the process allow most compounds to be extracted with little damage and denaturation (e.g., fragrance compounds used in perfumery). Because CO_2 is obtained as a byproduct of other industrial processes, it is inexpensive, and being a gas it is easily evaporated leaving no residue.

Supercritical water: Organic substances are insoluble in water. Many compounds are soluble in water when it becomes supercritical at 374°C and 218 atm. Hence, this clean and cheap solvent is used as a green solvent for many synthetic reactions.

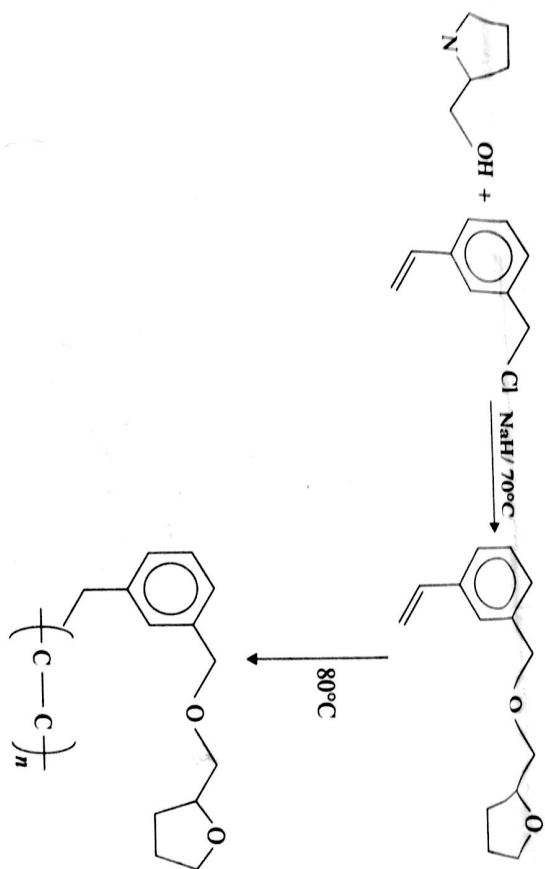
Reactions in aqueous phase: The use of ordinary water for organic reactions was unknown till the middle of the 20th century. However, replacement of organic solvents

with eco-friendly water has found success with many reactions, some of which may occur at higher rates because of its high polarity. Reactions carried out in aqueous medium include oxidations, reductions, epoxidations, polymerizations (with or without catalysts), and many name reactions. Li and Chan reported some case studies showing the innovative use of water as a reaction medium. For example, water with alcohol as co-solvent is used in Diels–Alder reactions. One example is shown here.



Reactions in solid phase: Large numbers of reactions occur in solid state without the solvent. These reactions are simple to operate and economical, and solvent-related pollution is avoided.

Immobilized Solvent material: Here the hazardous material is made immobilized so that its chance of release to environment can be minimized. For example, Hurter and Hatton developed a novel concept in which the hazardous substance under consideration such as THF is attached to a polymeric backbone using chlorinated styrene derivative. As THF remains attached to polymeric backbone is less likely to volatilize, it can be recovered easily by ultrafiltration.



THF attached with polymer backbone

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 methods should be carried out at ambient temperature and pressure.

Ex: Microwave irradiation, ultrasound energy (sono-chemistry)

CHAPTER

22

Green Chemistry

Green Chemistry - Outlines, Principles.

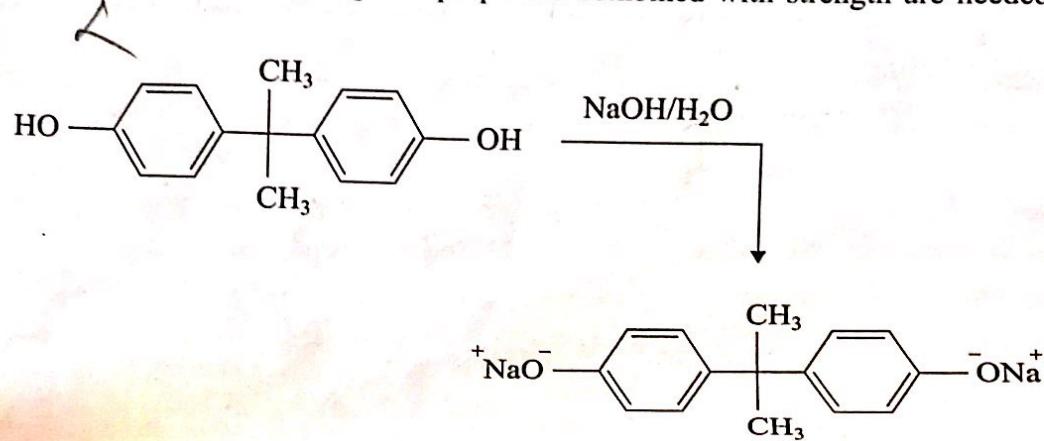
Chapter Outline

- Principles
- Examples of Green Chemistry in Industry
- Matrices to Express Greenness
- Green Chemistry and Catalysis
- Extra Element Detection in Organic Compounds (Safer Technique)
- R₄M₄ Principle
- Life Cycle Analysis

The term "Green Chemistry" was first coined by P. T. Anastas in 1991 during a special program launched by the United States Environmental Protection Agency (USEPA). As per him: It's more effective, it's more efficient, it's more elegant, it's simply better chemistry. Green chemistry incorporates a new approach to the synthesis, processing, and application of chemical substances in a manner so as to reduce threats to human health and the environment. It has changed the traditional concepts of efficiency of process that focus primarily on product yield in a process to the one that assigns economic value for eliminating waste at source and avoiding the use of toxic and/or hazardous substances. In other words, green chemistry is a proactive approach to pollution prevention. It targets pollution at the design stage, before it even begins.

Green chemistry may be defined as: The design of chemical products and processes that are more environmentally benign and reduce negative impacts to human health and the environment.

- Prevention:** It is better to prevent waste than to treat or clean up waste after it has been created.
- Atom economy:** Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product (discussed separately).
- Less hazardous chemical synthesis:** Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment. This principle can be explained by the following examples:
 - Polycarbonate is a class of polymers which find wide applications in cases where high optical properties combined with strength are needed. The most



Green's Theorem:

If $M, N, \frac{\partial M}{\partial y}, \frac{\partial N}{\partial x}$ are continuous and single valued functions in a region R enclosed by the curve C , then $\int_C (Mdx + Ndy) = \iint_R \left(\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right) dx dy$.

Note:

1. If $\frac{\partial M}{\partial y} = \frac{\partial N}{\partial x}$, the value of the integral $\int_C (Mdx + Ndy)$ is independent of the path of integration.

2. If R is a region bounded by a simple closed curve ' C ' then the area R is given by

$$\frac{1}{2} \int_C (xdy - ydx)$$

Problems on Green's Theorem:

Example: 1. Verify Green's theorem in the plane for $\int_C (x^2 dx + xydy)$, where C is the curve in the xy -plane given by $x = 0, y = 0, x = a$ and $y = a$ ($a > 0$).

Solution: by Green's theorem we have $\int_C (Mdx + Ndy) = \iint_R \left(\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right) dx dy$

comparing, we have $M = x^2$ and $N = xy$ and $\frac{\partial M}{\partial y} = 0$ and $\frac{\partial N}{\partial x} = y$ and $\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} = y$

$$\int_C (x^2 dx + xydy) = \iint_R y dxdy \text{ we need to evaluate both integrals.}$$

Let us evaluate the RHS integral, for the given region x and y varies from 0 to 1

$$\text{therefore, } \iint_R y dxdy = \int_0^a \int_0^a y dy dx = \int_0^a \left[\frac{y^2}{2} \right]_0^a dx = \int_0^a \frac{a^2}{2} dx = \frac{a^3}{2}$$

(i) along the line $OA, y = 0$ and $dy = 0$

$$\int_C (x^2 dx + xydy) = \int_0^a x^2 dx = \frac{a^3}{3}$$

(ii) along $AB x = a$ and $dx = 0$

$$\int_C (x^2 dx + xydy) = \int_0^a ay dy = a \left[\frac{y^2}{2} \right]_0^a = \frac{a^3}{2}$$

(iii) along $BC y = a$ and $dy = 0$

$$\int_C (x^2 dx + xydy) = \int_{-a}^0 x^2 dx = \left[\frac{x^3}{3} \right]_{-a}^0 = -\frac{a^3}{3}$$

(iv) along $CO x = 0$ and $dx = 0$ and $\int_C (x^2 dx + xydy) = 0$

Summing up all the integrals, we get $\frac{a^3}{3} + \frac{a^3}{2} - \frac{a^3}{3} + 0 = \frac{a^3}{2}$

Thus, $\int_C (Mdx + Ndy) = \iint_R \left(\frac{\partial N}{\partial x} - \frac{\partial M}{\partial y} \right) dx dy = \frac{a^3}{2}$, hence verified.

