

Future Trends in Green Chemistry

Challenges of Green Chemistry and Areas of Improvement towards sustainability:

Green chemistry aims to develop new chemical technology for designing new processes and products that minimize the use of toxic and hazardous materials. The challenges that face green chemistry are manifold, namely –

- i) development of new methods that are sustainable as well as cost-effective, with minimum negative impact on environment;
- ii) avoiding the use to materials detrimental to health and environment;
- iii) reducing, or preferably eliminating the formation of by-products and waste;
- iv) using safer alternatives to traditional catalysts or solvents.

The specific areas where the research in green chemistry is focussed are, among others,

- A] Oxidation reagents and catalysts,
- B] Biomimetic, multifunctional reagents,
- C] Combinatorial green chemistry,
- D] Solventless reactions
- E] Sustainable development.

Let us highlight these areas and advancements made therein one by one:

A] Oxidation reagents and catalysts

Oxidation reaction is one of the key chemical transformations usually needed in industries and laboratories around the globe. Most of the oxidations are still largely carried out with stoichiometric inorganic (or organic) oxidants such as Cr(VI) reagents, permanganate, manganese dioxide, and periodate, which, in general, lead to poor atom economy and add hazardous by-products in the environment.

Disadvantages/ Non-green context:

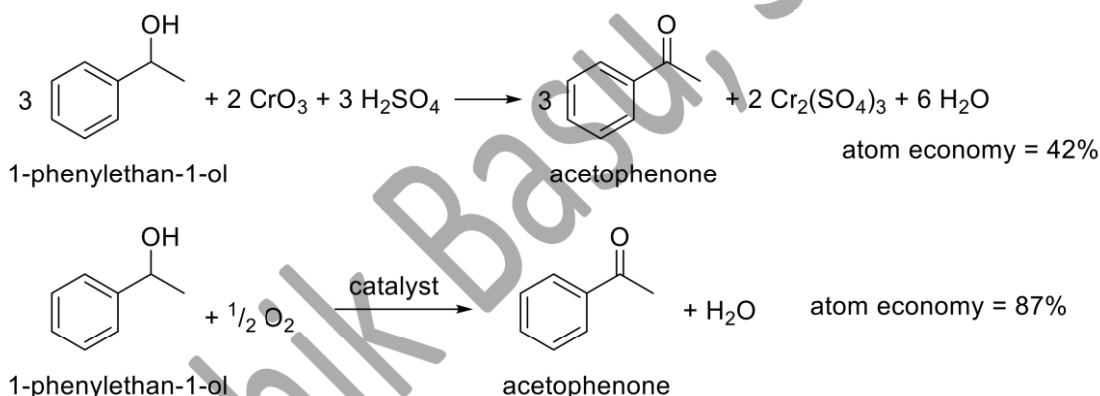
1. The oxidizers commonly used (mentioned above) are usually toxic. Use of these in large quantities, particularly in industrial scales poses a serious threat to environment and presents a health hazard.
2. Some oxidizers require delicate handling, making the process costly as expensive equipment are involved. Nonetheless, accidental damages from these chemicals are quite frequent.
3. The by-products of these reagents are also often toxic. When the oxidizer is used in stoichiometric amount, the oxidations are very poor in terms of atom economy and produce large amounts of by-products. These contribute to toxic waste which require special disposal.
4. Uncontrolled oxidations often is a nuisance, leading to wastage of valuable feedstock and formation of useless products.

5. Separation of the desired products from the undesired side products and oxidation by-products sometimes is challenging and involves tedious processes.
6. The chemoselectivity is sometimes not up to the mark with many conventional oxidants.
7. All of the above contribute to relatively poor yield of the desired product.

Green Approach in Oxidation:

1. Use of toxic heavy metals such as Cr(VI) should be avoided. Instead, if metal-based oxidation is a priority, more innocuous metals such as Fe(III) or Zn(II) can be used. Ideally, environmentally benign oxidizers such as O₂, H₂O₂ etc. should be used in conjunction with a suitable catalyst.
2. Toxic, environmentally untenable catalysts can be replaced by biocatalysts (such as enzymes) or of polymer-supported catalysts which are easily recyclable.
3. Nano-sized catalysts could be a solution to the problem associated with hazardous material production.
4. Modern techniques such as non-covalent derivatization (NCD) and co-crystal controlled solid state synthesis (C²S³) should be adopted, as much as possible.

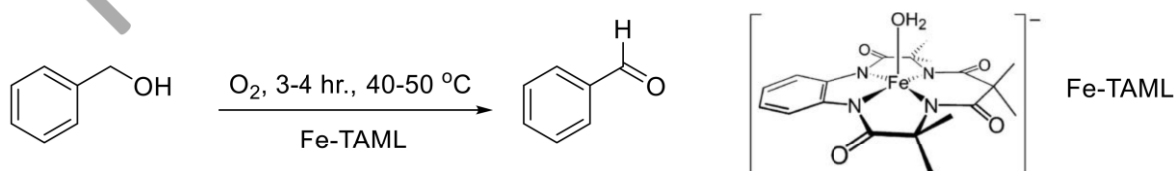
Case in point:



Examples of green oxidations:

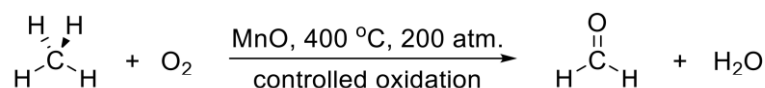
Oxidations using O₂ activated by catalysts:

1. Iron-based "Fe-TAML" catalysts (TAML: tetraamido macrocyclic ligands) activate environmentally benign oxidizing agents such as H₂O₂ and O₂, providing an alternative to polluting chlorine- and metal-based oxidants.

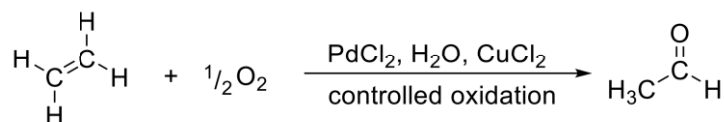


Fe-TAML-activated oxidants (like H₂O₂) can be used instead of dangerous ClO₂ gas in applications such as bleaching of kraft paper pulp, and deactivation of pesticides (fenitrothione) and biological warfare agents.

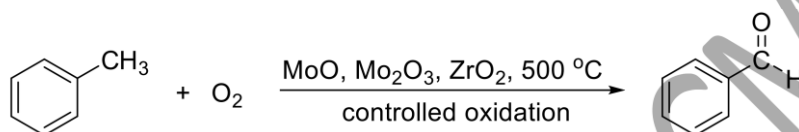
2. Production of formaldehyde by controlled oxidation of methane:



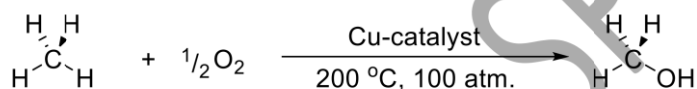
2. Production of acetaldehyde by controlled oxidation of ethene:



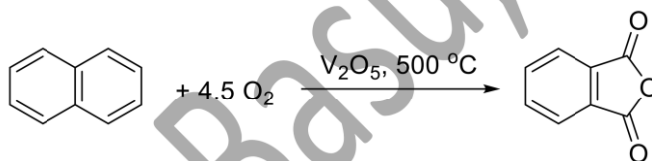
3. Production of benzaldehyde by controlled oxidation of toluene:



4. Production of methanol by controlled oxidation of methane:



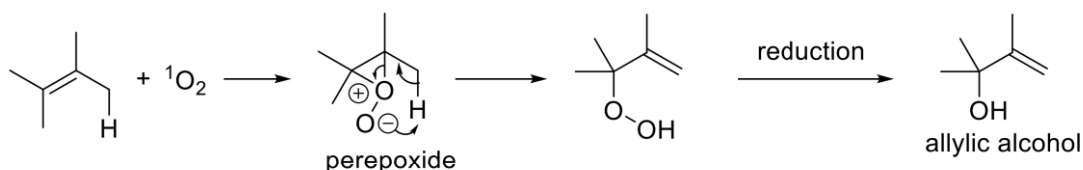
5. Production of phthalic anhydride by oxidation of naphthalene:



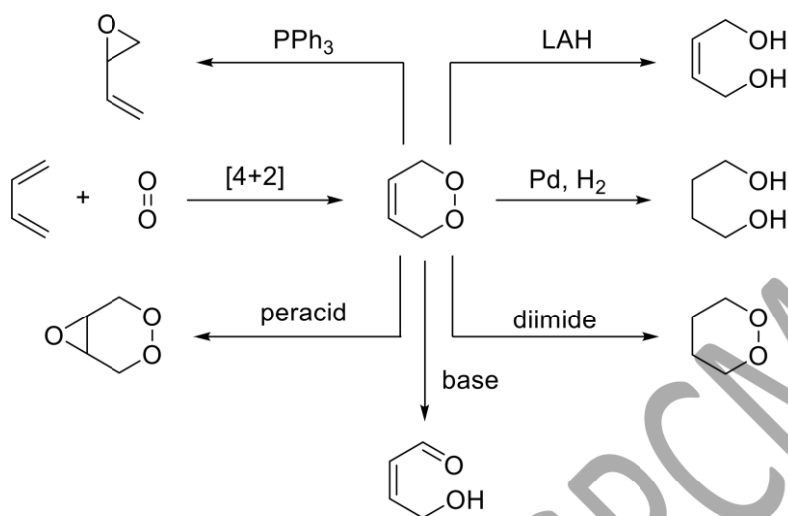
Oxidations using singlet oxygen: Singlet oxygen ($^1\Delta \text{O}_2$, 22 kcal/mol higher in energy) can be generated by shining light on a solution of oxygen in the presence of a triplet sensitizer like Methylene Blue or Rose Bengal. There are also several chemical methods of generating singlet oxygen, most notably the reaction of hydrogen peroxide with hypochlorite.

Singlet oxygen has a lifetime of under a second, but it is much more reactive towards organic compounds than is triplet oxygen, reacting readily with alkenes (ene reaction to form allylic hydroperoxides), dienes (cycloaddition to form 1,2-dioxanes), electron-rich aromatic compounds, phosphines, sulfides and selenides (to form oxides). Singlet oxygen is an electrophilic reagent (with a low-energy LUMO), and reacts more readily with electron-rich double bonds, and slowly or not at all with electron-poor ones. All these reactions must happen during the short lifetime of singlet oxygen before it decays to the ground state.

1. Production of hydroperoxides (precursor to alcohols) from alkenes (Schlenk ene reaction):

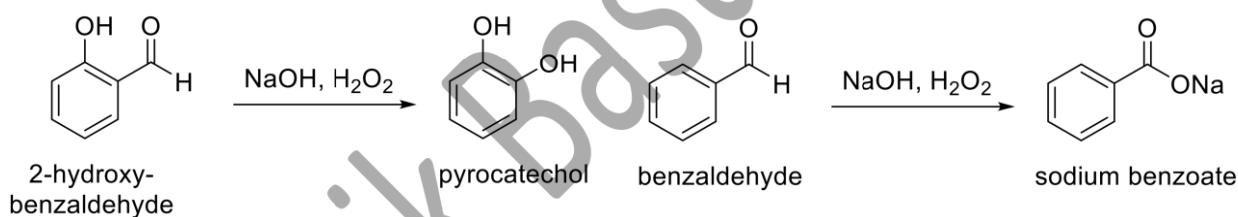


2. [4+2] cycloaddition with dienes and downstream functionalization: unlike triplet O_2 , 1O_2 is capable of participating in [4+2] cycloadditions with e-rich olefins and lead to peroxides which can be further manipulated to access a bunch of oxofunctionalized material:



Oxidations using hydrogen peroxide:

Numerous examples are there; a familiar one is the Dakin oxidation where a hydroxybenzaldehyde is oxidized to the corresponding phenolic compound, CHO being replaced by OH on the aromatic ring. The same reaction condition on benzaldehyde gives benzoic acid.



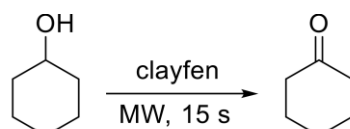
Oxidations using peracids:

Alkenes are efficiently epoxidized when reacted with peroxyacids (Prilezhaev reaction):

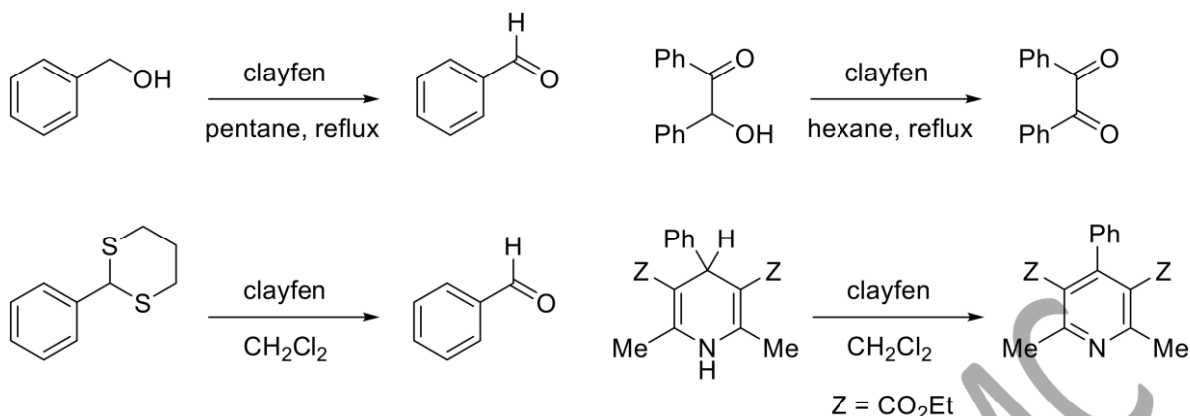


Oxidations using Clayfen:

Ferric nitrate impregnated into Montmorillonite K 10 is called clayfen. This is a valuable oxidizer, particularly in the rapid and efficient oxidation of secondary alcohols to ketones under MWI conditions:

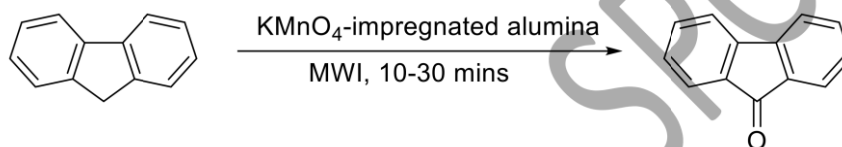


In addition, several other oxidative reactions are achievable:



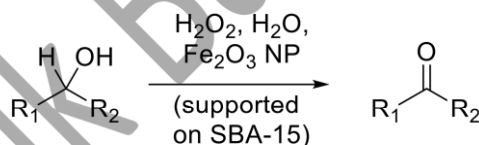
Oxidations using KMnO₄-impregnated alumina:

Solventless, MW-induced oxidation of fluorene to fluorenone can be done within 30 minutes.



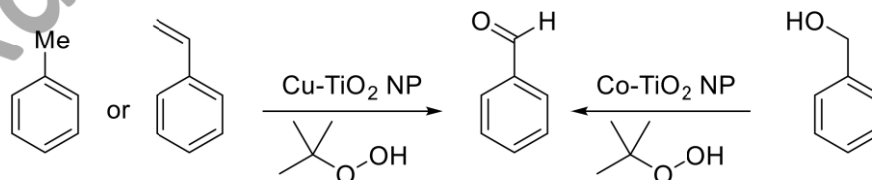
Oxidations using nanoparticles:

Nanoparticles provide astonishing catalytic activity due to its extremely small size (between 1 to 100 nm) and comparatively large surface area. Iron oxide (Fe₃O₄ and Fe₂O₃) nanoparticles show catalytic activity in oxidation of olefins and alcohols by O₂ or H₂O₂.



SBA-15 is a mesoporous silica material that has highly ordered nanopores and a large surface area. It is widely employed as catalyst supports, absorbents, drug delivery materials, etc.

Cu(II) and Co(II)-doped TiO₂ nanoparticles are shown to oxidize styrene, toluene or benzyl alcohol to benzaldehyde with excellent selectivity, with *tert*-butyl hydroperoxide as the oxidizer.



Oxidations using phase transfer catalysts:

Excluding oxygen, H₂O₂ is the most valuable oxidant with an atom efficiency of 47%, generating water as the only byproduct. Lipophilic quaternary ammonium salts such as Hex₄N⁺Br⁻ or Aliquat 336 are capable to efficiently extract H₂O₂ from the aqueous to the organic phase, allowing fast oxidation reactions under PTC conditions. In some cases, the H₂O₂ oxidation processes are

accelerated by the addition of transition metal co-catalysts such as molybdates or wolframates. Other oxidizers such as sodium hypochlorite is effectively used for oxidation of benzylic alcohols in presence of TBAB ($\text{Bu}_4\text{N}^+\text{Br}^-$):

