Current Trends in Pharmacy and Pharmaceutical Chemistry 2022;4(3):115–119

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Current Trends in Pharmacy and Pharmaceutical Chemistry

Journal homepage: https://www.ctppc.org/

Review Article

Role of catalyst in organic synthesis

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ARTICLE INFO

Article history:
Received 02-03-2022
Accepted 21-05-2022
Available online 20-08-2022

Keywords:
Catalysis
reaction
Homogeneous
Photocatalyst

ABSTRACT

Catalyst is a common word that comes across while studying chemistry especially while learning about chemical reactions. While some of the chemical reactions occur quickly, some take a long time and require extra materials or effort. In Chemistry, catalysts are defined as those substances which alter the rate of reaction by changing the path of reaction. Most of the time a catalyst is used to speed up or increase the rate of the reaction. However, if we go to a deeper level, catalysts are used to break or rebuild the chemical bonds between the atoms which are present in the molecules of different elements or compounds. In essence, catalysts encourage molecules to react and make the whole reaction process easier and efficient. The present review focuses on history, types and role of catalysis in organic reaction.

1. Introduction

Catalysis is one of the fundamental pillar of green chemistry, the development of chemical products and methods that minimises or reject the use and generation of hazardous substances. The design and use of new catalysts benefit and catalytic systems are simultaneously achieving the dual goals of environmental protection and economic benefit.Use of Catalysis in organic reactions providesnew reaction route, it can increase the stability of a transition state, reactivity of a nucleophiles, susceptibility of an electrophile to nucleophilic attack, leaving ability of a group by converting it into a weaker base,[1]

2. History

Catalyst is a term derived from Greek $\kappa\alpha\tau\alpha\lambda\acute{\upsilon}\epsilon\iota\nu$, meaning “to annul,” or “to unite,” or “to pick up.”In 1794 Elizabeth Fulhame chemist was first inventedthe term catalysis and it was designated in her book. Further in 1811Gottlieb Kirchhoff who was a Russian chemist utilized catalyst in first chemical reaction in organic chemistry. In 1835 Swedish chemist named JonsJakob Berzelius used the term catalysis to describe reactions that were sped up by certain substances.[2]

3. Types of Catalysts

3.1. *Positive catalysts*

Positive catalysts means that increase the rate of a chemical reaction. eg.Preparation of Ammonia (NH_3) by Haber’s method Iron oxide plays role of positive catalyst and increases the percentage yield of ammonia.

3.2. *Negative catalysts*

Negative catalyst that decrease the rate of chemical reaction. eg.By using Acetanilide of Hydrogen peroxide Decomposed intowater and oxygen, this act as a negative catalyst to decrease the rate of decomposition of hydrogen peroxide.

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https://doi.org/10.18231/j.ctppc.2022.019

3.3. *Promoter or accelerators*

A material or any chemical substance that increases the catalyst activity is known as a Promoter or accelerator.eg. In Haber's process molybdenum or a mixture of potassium and Aluminum oxides act as Promoters.

3.4. *Catalyst poisons or inhibitors*

Substances that reduces the activity of catalyst is called as catalyst poisons or inhibitors.eg. Hydrogenation of alkyne to an alkene, catalyst palladium is poisoned with barium sulphate in quinolone solution and the reaction is stopped at alkene level. The catalyst is known as Lindler's catalyst.

3.5. *Units*

"Katal" is the derived SI unit for measuring the catalytic activity of a catalyst.It's miles in addition quantified in moles per second.

4. Types of Catalysis

There are three types of catalyst according to the nature and the physical state of substance employed in the chemical reaction.

4.1. *Heterogeneous catalysis*

Heterogeneous catalysis means, the reacting substances involvedin reaction and catalyst employed in that reaction are not in the same state of matter. eg. In the production of Sulphuric acid (H_2SO_4) by Contact process**,** the major step is oxidation of Sulphur dioxide in this process sulphur dioxide and oxygen is a gas while vanadium pentoxide is a solid catalyst. In this oxidation process, reactants and catalysts are in different states of matter.

4.2. *Electrocatalysts*

Several types of metal-containing catalysts are used in electrochemistry especially in fuel cell engineering. These catalysts have one main role which is to enhance the rates of the halfreactions that occur in a fuel cell.

4.3. *Homogeneous catalysis*

The catalysis in which the catalyst employed in the reaction and the reactants are in the same state of matter that process is referred to as homogeneous catalysis. The effect of H+ on the esterification of carboxylic acids, such as the formation of methyl acetate from acetic acid and methanol, is one example of homogeneous catalysis.

4.4. *Photo catalysts*

Photo catalysis is the phenomenon wherein the catalyst is able to receive light (such as visible light) and be promoted to an excited state.

4.5. *Autocatalysis*

In this catalysis one of the reactants and reactor act as a catalyst and increases the rate of formation of product, means there is no specific catalyst that is added.eg. Oxidation of Oxalic acid by potassium Permanganate when permanganate is added to acidic solution oxidation of oxalate ions (or oxalic acid) occur. The reaction results in the formation of Mn^{2+} ions and it auto-catalyzes the reaction.[3–6]

5. The Role of Catalysis

In the manufacturing of inorganic compounds primarily waste material generated, fine chemicals and pharmaceuticals manufacture is uncontrolled with antiquated stoichiometric technologies. e.g. which readily come to mind are stoichiometric reductions with metals (Na, Mg, Zn, Fe) and metal hydride reagents ($LiAlH_4$, $NaBH_4$), oxidations with permanganate, manganese dioxide and chromium(VI) reagents and a wide variety of reactions, e.g. sulfonations, nitrations, halogenations, diazotizations and Friedel-Crafts acylations, employing stoichiometric amounts of mineral acids (H_2SO_4, HF, H_3PO_4) and Lewis acids ($AlCl_3$, $ZnCl_2$, BF_3).

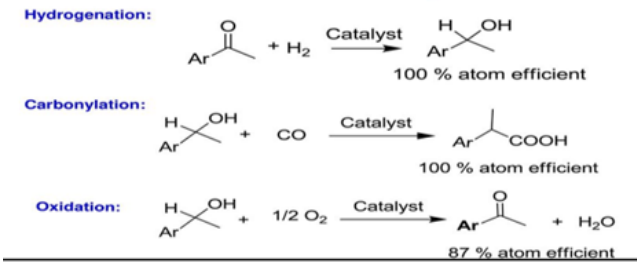
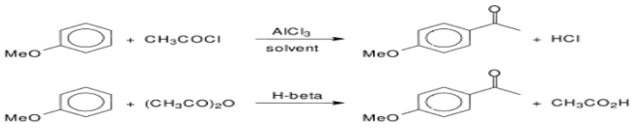


Fig. 1: Atom efficient catalysis process

5.1. *Solid acids and bases as catalysis*

Liquid mineral acids (HF, H_2SO_4) and a variety of Lewis acids use in chemical industry is the major source of waste. As waste streams containing large amounts of inorganic salts so they cannot easily be recycled and generally end up, via a hydrolytic work-up in this respect solid acids, such as zeolites, acidic clays and related materials, have many advantages. Solid acid catalyst is applicable in acid-promoted processes in organic synthesis it include various electrophilic aromatic substitution reaction, e.g. nitration, Friedel-Crafts alkylation, acylations, and numerous rearrangement reactions such as the Beckmann and Fries rearrangements. Friedel-Crafts acylations generally require more than one equivalent use of $AlCl_3$ or BF_3 this is due to the strong complexation of the Lewis acid by the ketone product. Zeolite beta is employed as a catalyst, in fixed-bed operation, for the acetylation of anisole with acetic anhydride, to give p-methoxyacetophenone (Figure 2). In original process acetyl chloride in combination with equivalent weight of $AlCl_3$ in a chlorinated hydrocarbon solvent, and generated aqueous effluent, containing $AlCl_3$, HCl, solvent residues and acetic acid, as a product. The Rhodia process is not only environmentally beneficial to the traditional process but also has more favourable economics. This is an important consideration that, catalytic chemistry, in addition to having obvious environmental benefits, is also economically more attractive.



Homogeneous	**Heterogeneous**
$AlCl_3 > 1$ equivalent	H-beta, catalytic & regenerable
Solvent	No solvent
Hydrolysis of products	No water necessary
Phase separation	-
Distillation organic phase	Distillation organic phase
Solvent recycle	-
85-95% yield	> 95% yield, higher purity
4.5 kg aqueous effluent per kg	0.035 kg aqueous effluent per kg
12 unit operations	3 unit operations

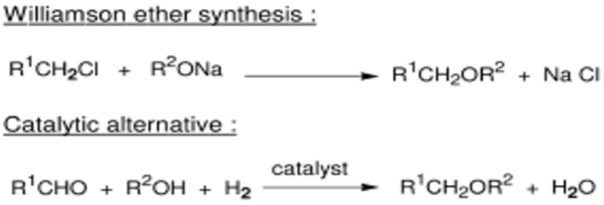
Fig. 2: Zeolite-catalysed vs classical friedal-craft acylation

5.2. *Catalytic Reductions*

Catalytic hydrogenation completely represents the concept of accuracy in organic synthesis. Molecular hydrogen is a clean and abundant raw material and catalytic hydrogenations are generally 100% atom efficient, with the exception of a few examples, e.g. nitro group reduction, in which water is formed as a co-product. They have a tremendously broad scope and exhibit high degrees of chemo-, regio-, diastereo and enantioselectivity. The synthetic process of catalytic hydrogenation is very well reported in the words of Rylander. Catalytic hydrogenation is one of the most useful and resourceful tool available to the organic chemist. In 1852 Williamson synthesis of ethers is firstly described. Catalytic alternative to the Williamson synthesis, involving reductive alkylation of an aldehyde (Figure 3) has been reported. This avoids the formation of NaCl as by product, depending on the production volume. Furthermore, the aldehyde may, in some cases, be more readily available than the corresponding alkyl chloride.[1,7–9]

5.3. *Enzyme Technology in biocatalytic reduction*

The use of isolated enzymes or cell extracts is highly preferable. In this case, for their efficient recycling, two strategies are feasible. These are depicted in Figure 4.



$$R^1CH_2Cl + R^2ONa \longrightarrow R^1CH_2OR^2 + NaCl$$

$$R^1CHO + R^2OH + H_2 \xrightarrow{\text{catalyst}} R^1CH_2OR^2 + H_2O$$

Fig. 3: Williamson ether synthesis and catalytic alternative

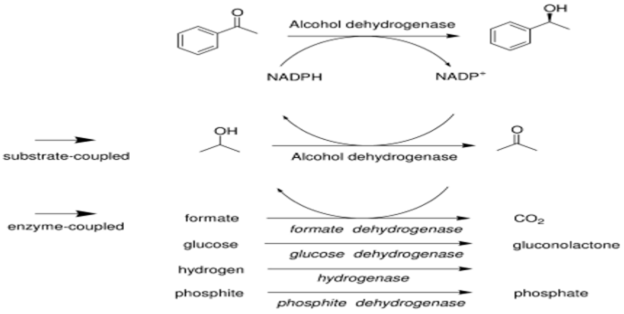


Fig. 4: C-factor recycling during bio-reduction process.

In the first case for the completion of reduction process, only one enzyme is required and additional alcohol is added to complete the reduction. This coupled substrate-system stand a strong similarity to transition metal transfer hydrogenation is called Meerwein-Ponndorf-Verley reaction. In the second approach, in combination with a second enzyme, namely formate dehydrogenase, glucose dehydrogenase, hydrogenaseorphosphite dehydrogenase a variety of reducing agents are used, such as formate, glucose, H_2 or phosphate respectively. In the first approach, one enzyme is required to convert both substrate (ketone) and by-product (alcohol). This by product is removed by distillation process. In whole cell preparation the alcohol dehydrogenases from Rhodococcus ruber is employed. Using this system, a variety of methyl ketones, ethyl ketones and chloromethyl ketones could be reduced with Prelog preference. It is also worth noting that this system has been used in a reduction as well as an oxidation mode.[1,10–12]

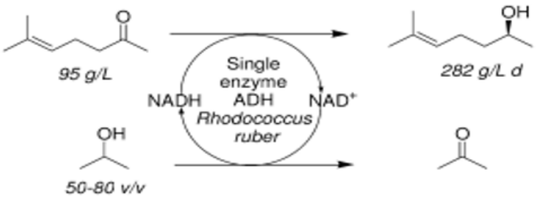


Fig. 5: 5 6-Methyl-hept-5-en-2-one reduction andsimulteneous NAD+ regeneration using alcohol dehydrogenase from Rhodococcus rubber.

5.4. Catalytic oxidation

Catalytic oxidation is the possess in which the compounds was oxidize using catalysts. The Common example involves oxidation of organic compounds by the oxygen in air. Such processes are carried out on a large scale for the remediation of pollutants, production of valuable chemicals and energy. By partial oxidation of alkanes and alkenes with dioxygen, high-value intermediates such as carboxylic acids, aldehydes, ketones, epoxides, and alcohols are obtained, in petrochemistry. These intermediates are essential to the production of consumer goods. There are two challenges in Partial oxidation the first is that the most favored reaction between oxygen and hydrocarbons is combustion. The second challenge is the considerable difficulty to activate dioxygen.[13]

$$\mathrm{ROH}\ \xrightarrow[\substack{\text{Green solvent } (H_2O)\\ \text{Green Catalyst}}]{\substack{\text{Green Oxidant}\\ (O_2 \text{ or } H_2O_2)}}\ \begin{array}{l}\text{Aldehydes}\\ \text{Ketones}\\ \text{Carboxylic acids}\end{array}$$

5.5. Catalysis carbon-carbon bond formation

It is an important catalytic methodology for generating C–C bonds is carbonylation. e.g, for the production of acetic acid by rhodium-catalysed carbonylation of methanol. This reaction is increasingly being applied to fine chemicals manufacture because these reactions are 100% atom efficient. The well-known example of this is Hoechst-Celanese process for the manufacture of the analgesic, ibuprofen. In this process ibuprofen is produced in two catalytic steps (hydrogenation and carbonylation) from p-isobutylactophenone (Figure 6) with 100% atom efficiency.[14]

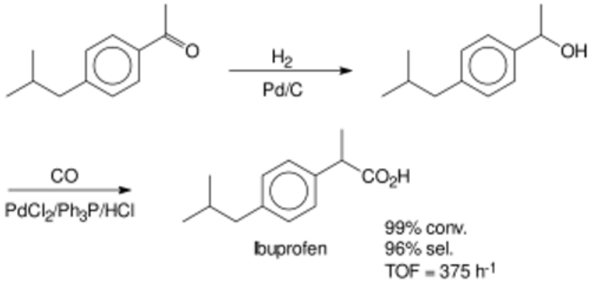


Fig. 6: Hoechst-celanese process for ibuprofen.

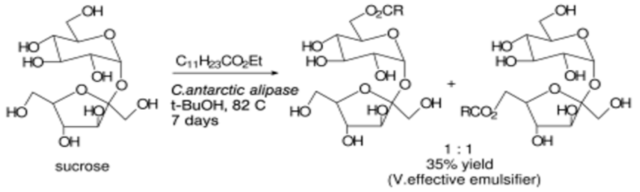


Fig. 7: Synthesis of abioemulsifier from renewable raw material.

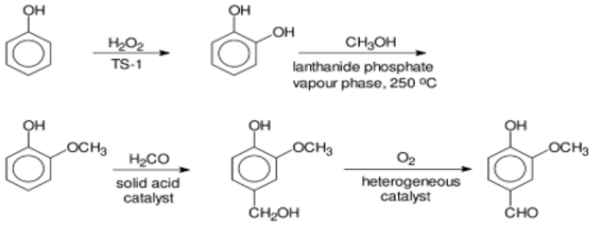


Fig. 8: Rhodia vanillin process.

5.6. Hydrolysis

Hydrolysis reactions are simple to carry out and they have a good equilibrium, because water is used as solvent. This also has the application of green chemistry, because water is an environmentally favourable solvent. However, traditional hydrolysis reactions have many disadvantages. They are commonly performed with concentrated, corrosive acids or bases. These reaction need to be neutralized at the end of the reaction, generating salts as waste. In addition, high temperatures are often required, wasting much energy. If the substrate submitted to the hydrolysis reaction has more than one functional group lack of selectivity becomes a major problem, delicate structures might even be completely degraded. At the end of the reaction the product needs to be separated from the water, which is often difficult and energy consuming, especially if it involves a distillation. Furthermore, hydrolysis reactions are never 100% atom efficient, depending on the group that is cleaved off they can even be quite atom inefficient. From a green point of view much can still be improved in traditional hydrolysis reactions. Different approaches, such as solid acids and bases have been developed to address some of these problems.[15–17]

5.7. Catalysis in novel reaction media

Organic reactions are generally performed in a solvent because of reactions proceed faster and more smoothly when the reactants are dissolved in solvents due to diffusion. Although reactions in the solid state are known they are often condensations in which a molecule of water is formed and reaction takes place in a thin film of water at the boundary of the two solid surfaces. It is worth noting, however, that not all of the reactant(s) have to be dissolved and reactions can often be readily performed with suspensions. Indeed, so-called solid-to-solid conversions, whereby a reactant is suspended in a solvent and the product precipitates, replacing the reactant, have become popular in enzymatic transformations. In some cases, the solvent may be an excess of one of the reactants. In this case the reaction is often referred to as a solvolysis, or, when the reactant is water, hydrolysis.[1]

5.8. Chemicals from renewable raw materials

Another important purpose of green chemistry is the utilisation of renewable raw materials, i.e. derived from biomass, rather than crude oil. The processes used for the conversion of renewable feed stocks mainly carbohydrates but also triglycerides and terpenes should produce minimal waste, i.e. they should preferably be catalytic. In the processes of a biocatalyst whole microbial cells or an isolated enzyme is used to catalyse a transformation of a particular substrate. When growing microbial cells are used this is referred to as precursor fermentation alternatively, one can employ de novo fermentation to produce chemicals directly from biomass. This is known as white biotechnology, as opposed to red biotechnology (biopharmaceuticals) and green biotechnology (genetically modified crops). White biotechnology is currently the focus of considerable attention and is perceived as the key to developing a sustainable chemical industry. Example of a product derived from renewable raw materials is the bioemulsifier, which consists of a mixture of sucrose fatty acid esters. The product is prepared from two renewable raw materials sucrose and a fatty acid which is biodegradable. In the current process the reaction is catalysed by a mineral acid, which leads to a rather complex mixture of mono- and di-esters. Hence, a more selective enzymatic esterification (Figure 7) would have obvious benefits.[1]

5.9. Process integration and cascade catalysis

The widespread application of chemo and biocatalytic methodologies in the manufacture of fine chemicals is resulting in a gradual disappearance of the traditional barriers between the sub disciplines of homogeneous and heterogeneous catalysis and biocatalysis. Example is the Rhodia process for the manufacture of the flavor ingredient, vanillin. The process involves four steps, all performed with a heterogeneous catalyst, starting from phenol (Figure 8). Overall, one equivalent of phenol, H_2O_2, CH_3OH, H_2CO and O_2 are converted to one equivalent of vanillin and three equivalents of water.[1,18,19]

6. Source of Funding

None.

7. Conflict of Interest

None.

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Cite this article: Amrutkar RD, Bhalerao SS, Bhoir AS, Bhusare RH, Bodhare SS, Borse JN. Role of catalyst in organic synthesis. *Curr Trends Pharm Pharm Chem* 2022;4(3):115-119.