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The role of catalysis in the design, development, and implementation of green chemistry

Paul T. Anastas *, Lauren B. Bartlett, Mary M. Kirchhoff, Tracy C. Williamson

Office of Pollution Prevention and Toxics, U.S. Environmental Protection Agency, Mail code 7406, 401 M Street S.W., Washington, DC 20460, USA

Abstract

Green chemistry is the design of chemical products and processes which reduce or eliminate the use and generation of hazardous substances. In the last decade, green chemistry has been recognized as a new approach to scientifically based environmental protection. Catalysis has manifested its role as a fundamental tool in pollution prevention. While catalysis has long been utilized in increasing efficiency, yield, and selectivity, it is now also recognized as accomplishing a wide range of green chemistry goals. ©2000 Elsevier Science B.V. All rights reserved.

Keywords: Catalysis; Green chemistry; Environmental protection

1. Introduction

Throughout the 1990s, there has been a move away from the ‘command and control’ approach to environmental protection to a more scientifically-based and economically beneficial approach known as green chemistry. Rather than simply complying with regulatory prescriptions, which often carry a heavy financial burden, many companies are now embracing green chemistry as a way to not only exceed required regulatory controls, but to do so in a manner that is profitable.

Green chemistry utilizes a set of principles that reduces or eliminates the use or generation of hazardous substances in the design, manufacture, and application of chemical products [1]. The 12 principles [2] outlined in Table 1 should be understood in terms similar to other criteria historically used by chemists such as yield, number of total synthetic steps, or selectivity. It may be impossible to maximize all of the factors simultaneously, so trade-offs may be necessary to optimize the various criteria for highest benefit. All aspects of a synthesis must be considered when designing a ‘greener’ process. Environmental gains will not be realized if pollution is simply shifted from one step to another.

This paper focuses on the use of catalysis as a primary tool for achieving all of the 12 principles of green chemistry. The examples provided demonstrate that catalytic procedures have been effectively implemented to accomplish several of the green chemistry principles simultaneously; all of the reactions presented address principle 9 through their use of catalytic reagents. These examples encompass the full range of catalytic science, from heterogeneous to homogeneous catalysis, from exploratory research to full industrial commercialization. By presenting some exemplary case studies in catalysis for green chemistry, the reader can see the potential for the use of catalysis in achieving both economic and environmental goals.

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* Corresponding author.

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Table 1
The 12 principles of green chemistry

1. It is better to prevent waste than to treat or clean up waste after it is formed
2. Synthetic methods should be designed to maximize the incorporation of all materials used into the final product
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment
4. Chemical products should be designed to preserve efficacy of function while reducing toxicity
5. The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used
6. Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure
7. A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable
8. Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible
9. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents
10. Chemical products should be designed to preserve efficacy of function while reducing toxicity
11. Analytical methodologies need to be developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances
12. Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions and fires

2. Discussion

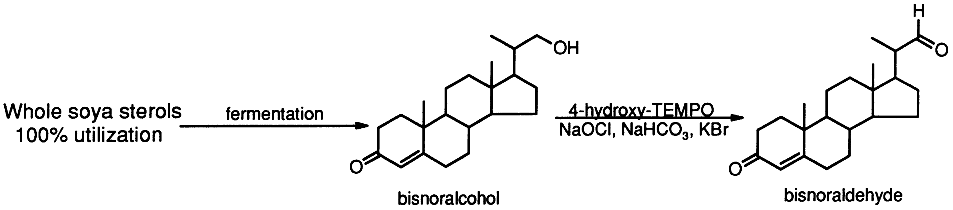
2.1. *Principle 1: It is better to prevent waste than to treat or clean up waste after it is formed*

Perhaps this principle is the most intuitively obvious. Waste prevention brings both environmental and economic benefits. By consciously designing a reaction that does not generate waste, the need for separation, treatment, and disposal of hazardous substances is eliminated.

In collaboration with Eni, Tundo and coworkers [3,4] have demonstrated applications for dimethylcarbonate (DMC) as an alternative to phosgene in carbonylation reactions, and as a substitute for methyl chloride and dimethyl sulfate in methylation reactions. The DMC process generates no organic by-products or salts and demonstrates excellent selectivity when used with environmentally friendly catalysts such as zeolites and K_2CO_3. While the traditional synthesis of DMC also utilized phosgene, there is now an environmentally benign process which uses oxidative carbonylation of methanol [5,6]. Methylation reactions using DMC rather than phosgene also fulfill principles 3 (non-toxic reagents) and 12 (accident prevention).

In industrial applications, the oxidation of alcohols to carbonyl groups traditionally employs a heavy-metal catalyst, a process that generates a significant amount of hazardous waste. Pharmacia and Upjohn [7] have developed an alternative method that employs bleach (NaOCl) and a catalyst/co-factor system. These reagents are used to convert bisnoralcohol to bisnoraldehyde (Scheme 1), an intermediate in the synthesis of progesterone and corticosteroids. This process utilizes soya sterol feedstock as a starting material, produces a non-toxic aqueous waste stream and a recoverable organic waste stream, and avoids toxic reagents, such as organic peroxides and organoselenium compounds. Principles 3 (non-toxic reagents) and 7 (renewable feedstocks) are addressed by this process as well.

The pulp and paper industry employs chlorine oxidants to bleach pulp. As a result, chlorine-containing organics, a class of compounds with toxicity concerns, are produced as by-products. The development of a new iron catalyst/hydrogen peroxide system (Fig. 1) by Collins [8] permits the chlorine-free bleaching of paper. These versatile catalysts activate peroxide for pulp bleaching in water from neutral to basic pH, over a temperature range of 0–90°C. The catalysts show a greater selectivity for lignin over cellulose oxidation than existing totally-chlorine-free technologies. In addition to preventing waste, this innovative process also generates less-toxic substances (principle 3) and uses a safer oxidizing agent (principle 12). Although not commercially viable at this point, this catalytic process has the potential to eliminate chlorine bleaching from the pulp and paper industry.



Scheme 1.

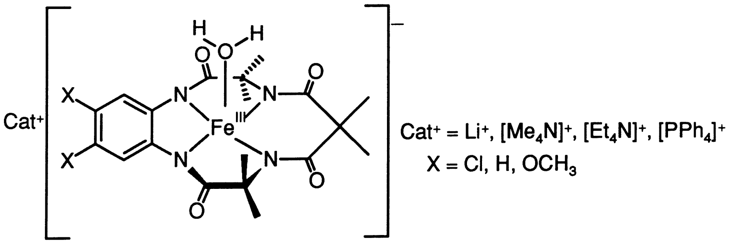


Fig. 1. Iron catalyst/hydrogen peroxide system.

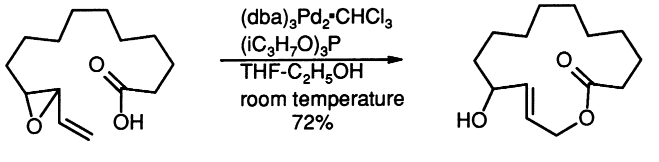
2.2. Principle 2: Synthetic methods should be designed to maximize the incorporation of all materials used into the final product

Traditionally, chemists have judged the success of a reaction by percent yield of product formed. This narrow focus ignores the quantity and nature of by-products generated by the reaction. The concept of atom economy [9] considers the efficiency with which the reagents are incorporated into the final product. Two well-known reactions, the Diels–Alder and Wittig reactions, can be used to illustrate the concept of atom economy. The Diels–Alder reaction is 100% atom efficient; all of the atoms in the diene and dienophile are included in the final product. In contrast, the Wittig reaction is inherently non-atom economical. A single methylene group is incorporated into the alkene product, with accompanying loss of the trialkylphosphine oxide by-product.

The work of Trost and coworkers [10] exemplifies the use of catalysis in maximizing atom economy. A variety of palladium catalysts have been used to effect allylic alkylation reactions. Macrolactones, for example, can be obtained from the corresponding carboxylic acid in a palladium-catalyzed process that is 100% atom efficient (Scheme 2). As the reaction occurs at room temperature, this synthesis addresses principle 5 (minimize energy use) as well.

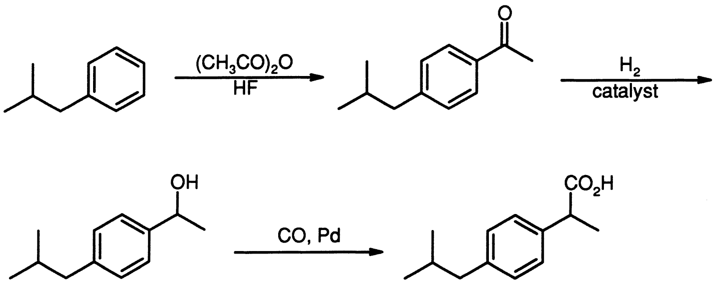
Ibuprofen is a widely-used analgesic marketed under the well-known brand names Advil$^{\text{TM}}$ and Motrin$^{\text{TM}}$. Traditional synthesis of ibuprofen has utilized six stoichiometric steps incorporating less than 40% atom utilization. BHC [11] has designed a catalytic synthesis that requires only three steps, with atom economy reaching 80% (99% with recovered acetic acid) (Scheme 3). The HF, which serves as both catalyst and solvent, is recovered and recycled with greater than 99.9% efficiency. The BHC ibuprofen process illustrates the compromises that may be necessary in pollution prevention. While atom economy is doubled, the synthesis uses a hazardous catalyst/solvent in the form of HF. With recovery of HF, however, the new process represents an improvement over the traditional synthesis of ibuprofen. The technology has been commercialized since 1992 at the BHC facility in Bishop, Texas.

Lanthanides can be used as highly selective catalysts in both Diels–Alder and aza-Diels–Alder reactions. Wang and coworkers [12] have used scandium triflate as catalyst in the Diels–Alder reaction of naphthoquinone and cyclopentadiene (Scheme 4). The *endo* product is produced exclusively in 93% yield. The catalyst is stable in the aqueous solution, and can be recovered and reused following extraction of the product.

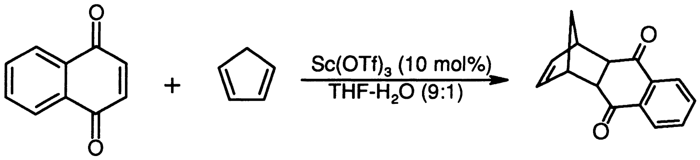


100% atom economy

Scheme 2.



Scheme 3.



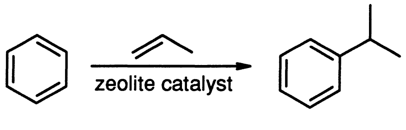
93% yield, endo/exo = 100/0

Scheme 4.

2.3. *Principle 3: Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment*

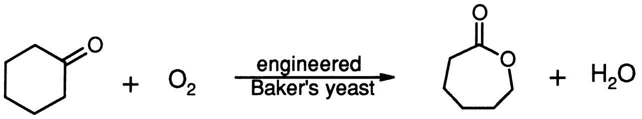
Risk is a function of both hazard and exposure and, therefore, risk can be reduced by minimizing either of these parameters. While exposure controls can fail, reducing intrinsic toxicity succeeds in eliminating risk by eliminating hazard. Reactions that utilize non-toxic reagents and yield non-toxic products are preferable to those that use or generate hazardous substances, from both environmental and often economic perspectives. Reaction and process design should consider the use of safer alternatives wherever possible.

One good example of this approach is the manufacture of cumene. Approximately 7 million metric tons of cumene are produced annually on a global scale. The traditional cumene synthesis employs benzene alkylation with propene over a solid phosphoric acid or aluminum chloride catalyst. Both catalysts are corrosive and are categorized as hazardous wastes. A zeolite catalyst is featured in the Mobil/Badger cumene process [13] (Scheme 5). The catalyst is environmentally inert and gives high yields of product. The new process generates less waste (principle 1), requires less energy (principle 6), and employs a less corrosive catalyst (principle 12).



Scheme 5.

The Baeyer–Villiger is a classic organic reaction for converting a ketone into a lactone. The most commonly used reagent for this transformation is *m*-chloroperoxybenzoic acid (mCPBA), a substance



Scheme 6.

that is shock-sensitive and explosive. Stewart [14] has used genetically-engineered Baker's yeast to effect the same transformation (Scheme 6). Yeast is a safe, non-pathogenic organism that biocatalyzes the oxidation of the ketone with atmospheric O_2. The reaction is run in an aqueous medium; water is the only by-product formed. In addition to principle 3, the enzymatic Baeyer–Villiger reaction satisfies principle 5 (benign solvents) and principle 12 (accident prevention). The scope of this reaction is currently being investigated.

2.4. Principle 4: Chemical products should be designed to preserve efficacy of function while reducing toxicity

An increased understanding of reaction mechanisms and toxicology allows chemists to better predict which compounds/functional groups may pose an environmental hazard. This information assists in the design of safer chemicals while maintaining the desired purpose of the product. This is true even in cases where the function of the product is toxicity (e.g., pesticides). Examples of safer chemical design can be seen in a number of chemical classes.

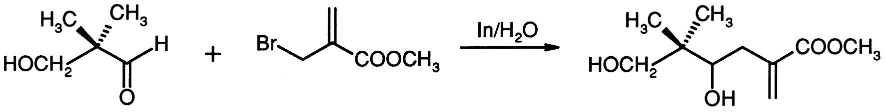
Gross has succeeded in synthesizing γ-poly(glutamic acid) via microbial fermentation from renewable feedstocks, such as glucose [15,16]. This water-soluble polymer is a biodegradable polyanion that is a suitable replacement for polyacrylic acid, a non-biodegradable polyanion that is persistent in nature. Principles 7 (renewable feedstocks) and 10 (biodegradability) are addressed by this process.

Another example is broad-spectrum insecticides, which are widely used to control insects for human-health and agricultural reasons. Problems associated with insecticide use include toxicity to other organisms, bioaccumulation, and the development of resistance on the part of some insects. Pheromones, the volatile chemicals released by insects, can be used for pest control. Sex pheromones, for example, may be used to disrupt the mating cycle of insects. However, pheromones are not as widely used as other insecticides due to the high cost of manufacturing. This economic challenge has been addressed by Knipple, who has explored the enzyme-catalyzed synthesis of Lepidopteran (moth) pheromone precursors [17]. Acyl-CoA desaturases, isolated from the glands of adult female moths, catalyze the formation of key pheromone intermediates. Pheromones offer distinct advantages over broad-spectrum insecticides. They are non-toxic and environmentally benign, specific to a target species, and less likely to induce resistance on the part of the insect. Replacement of insecticides by pheromones will be hastened through the design of more affordable synthetic methods.

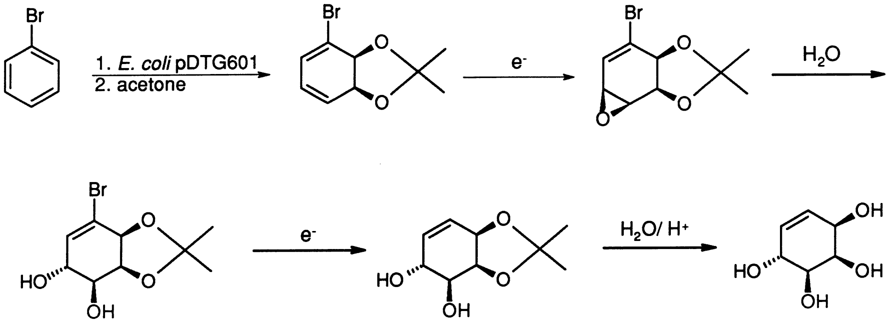
2.5. Principle 5: The use of auxiliary substances (e.g. solvents, separation agents, etc.) should be made unnecessary wherever possible and, innocuous when used

Auxiliary substances are used to promote a reaction, but are not incorporated into the final product. As such, they become part of the waste stream and may pose an environmental hazard. Certain chlorinated organic solvents, for example, are suspected human carcinogens, while chlorofluorocarbons (CFCs) are known to deplete the stratospheric ozone layer. When a solvent is necessary, benign solvents, such as water or supercritical carbon dioxide, should be employed wherever possible. Reaction design should also consider the means used to separate products and reactants at the end of the process, and evaluate the use of environmentally-friendly separation techniques.

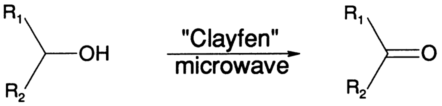
Coupling reactions may be conducted in aqueous media with an indium catalyst, as demonstrated by Paquette [18] and Li [19]. Indium is an ideal catalyst for these carbon–carbon bond-forming reactions (Scheme 7): it is stable in boiling water and base; does not form oxides upon exposure to air; is relatively non-toxic; and can readily be recovered and reused. Switching



Scheme 7.



Scheme 8.



Scheme 9.

from an organic solvent to water reduces air emissions and produces a cleaner waste stream.

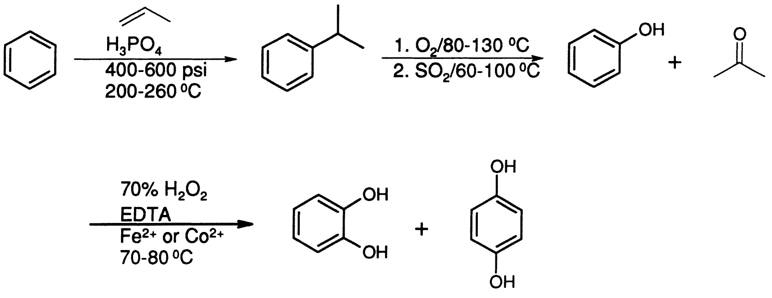
The synthesis of conduritol C, an intermediate in the syntheses of many carbohydrates, has been accomplished by Hudlicky and coworkers through a combination of biocatalysis and electrochemistry [20]. As depicted in Scheme 8, bromobenzene is functionalized in an enzymatic process using modified *E. coli*. Electrochemical methods conducted in water complete the reaction without the use of traditional reagents, such as peroxyacids and metal hydrides. The need for organic solvents is eliminated. Waste is prevented at the outset by replacing oxidation/reduction reactions with enzymatic and electrochemical techniques (principle 1).

Some reactions may actually be run under solvent-free conditions. Varma [21] has used microwave activation to oxidize alcohols to carbonyl compounds in the absence of solvent (Scheme 9). This process eliminates the need for traditional oxidizing agents, such as CrO_3 and $KMnO_4$. The neat reactants are combined in the presence of a catalyst or catalyzed by the surfaces of recyclable supports. Alumina, silica, and iron(III)nitrate-clay (clayfen) are some of the recyclable supports used in these reactions. Condensation and cyclization reactions have also proven successful under these solventless conditions.

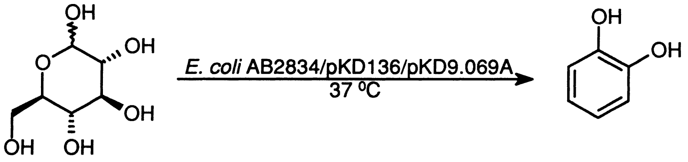
2.6. Principle 6: Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure

In addition to the potential for environmental harm inherent in a particular process, the energy required to carry out a synthesis also carries an environmental cost. Energy usage comes in many forms: heating, cooling, sonication, high pressure, vacuum, and energy needed for separation and purification of products. Catalysis provides an excellent tool for lowering energy requirements in a particular reaction.

GE Plastics has developed a catalyst that provides numerous environmental benefits in the synthesis of its ULTEM® thermoplastic resin [22]. Compared to the old system, the new process uses 25% less energy per pound of resin, consumes 50% less catalyst, generates 90% less organic waste for off-site disposal, and produces 75% less waste in the manufacture of the catalyst itself. Further refinements to the process will eliminate the need for a thermal oxidizer.



Scheme 10.



Scheme 11.

A catalytic process enables the Donlar Corporation [23] to polymerize thermal polyaspartate (TPA) at a lower temperature, thus decreasing energy demands. In addition, TPA is non-toxic, environmentally safe, and biodegradable, making it a viable alternative to polyacrylic acid (PAC), which is not biodegradable. The catalytic synthesis of TPA illustrates principle 4 (reduce toxicity) and principle 10 (biodegradability).

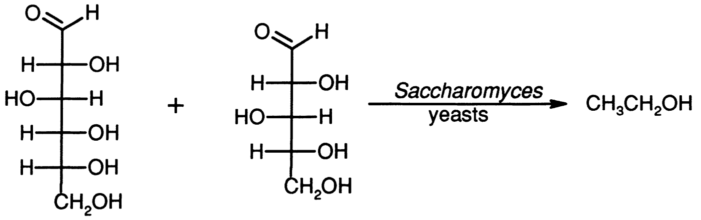
2.7. Principle 7: A raw material of feedstock should be renewable rather than depleting wherever technically and economically practicable

The petroleum industry serves as the starting point for the vast majority of organic syntheses. Yet, we are rapidly depleting our petroleum reserves and must look for alternative feedstocks if we are to develop a sustainable chemical industry. Typically, renewable feedstocks are plant-based materials, although any substance that can be regenerated in a reasonable amount of time (years rather than centuries or millennia), such as CO_2, may be considered renewable.

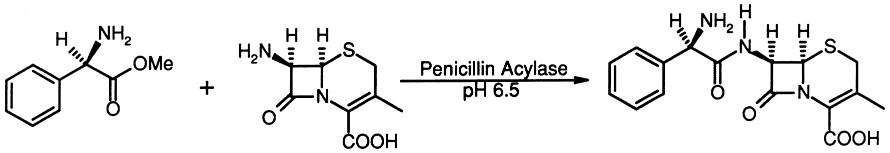
Draths and Frost [24,25] have utilized renewable feedstocks in the synthesis of such valuable chemical products as adipic acid and catechol. These synthetic schemes employ biocatalysis in the form of genetically-engineered microbes. The traditional synthesis of catechol (Scheme 10) begins with benzene, a known carcinogen, which is obtained from petroleum, a non-renewable feedstock. Using genetically-engineered *E. coli*, catechol may be obtained in a single step from D-glucose (Scheme 11). The biocatalytic pathway eliminates the use of hazardous substances present in the synthesis of catechol (principle 3) and decreases the energy demands of the reaction (principle 6).

Biocatalysis has proven effective in converting biomass to ethanol. Ho and coworkers [26] have designed recombinant *Saccharomyces* yeasts to simultaneously ferment glucose and xylose, present in cellulosic biomass, to ethanol (Scheme 12). Cellulosic biomass is a renewable feedstock, encompassing materials such as grasses, woody plants, and agricultural and forestry residues. Ethanol is recognized as a supplement to and replacement for gasoline and has the potential to reduce our dependence on imported oil.

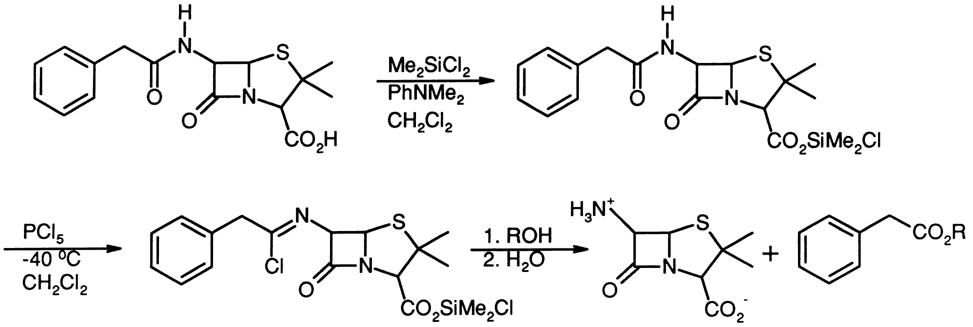
A relatively untapped source of renewable feedstocks is waste biomass. These waste resources include sewage sludge, municipal solid waste, agricultural residues, and manure. Holtzapple has used rumen microorganisms in an anaerobic fermentor to convert waste biomass into volatile fatty acid salts, which may be concentrated and transformed into chemicals or fuels [27]. Acidification of the salts yields acetic, propionic, and butyric acids. Thermal conversion of the salts produces ketones, which may be hydrogenated to the corresponding alcohols. Commercial



Scheme 12.



Scheme 13.



Scheme 14.

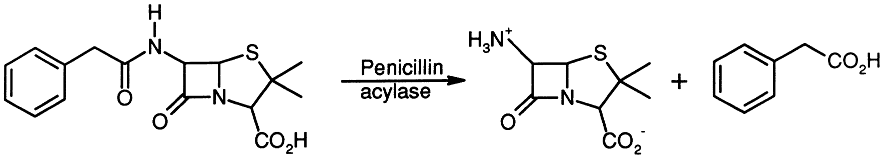
utilization of waste biomass eliminates disposal costs, both economic and environmental, and conserves non-renewable resources, such as petroleum.

2.8. Principle 8: Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible

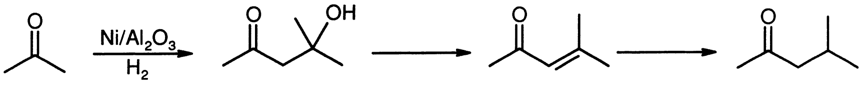
It is often necessary when executing a multi-step synthesis to protect a sensitive functional group from unwanted reaction or to temporarily convert a compound to its salt for ease of separation. Both of these actions, however, require additional steps with attendant increases in materials, time, and energy. Catalytic reactions often can offer enhanced selectivity that minimizes the number of modifications required in a reaction sequence.

Enzymes are known for their high selectivity, but are not widely used in industry due to their instability, solvent incompatibility, and high cost. Altus Biologics [28] has developed cross-linked enzyme crystals (CLECs) to increase the versatility of enzymes in organic reactions. Unlike free enzymes, CLECs can withstand extremes of temperature and pH and exposure to both aqueous and organic solvents. The CLEC-mediated synthesis of the antibiotic cephalexin eliminates the need for N-protection of D-phenylglycine (Scheme 13).

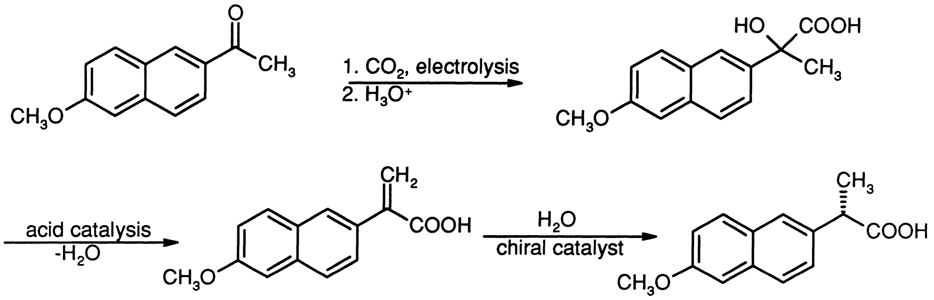
Biocatalysis has also proven effective in the synthesis of 6-aminopenicillanic acid (6-APA). The classic synthesis of this antibiotic intermediate requires protection of the carboxyl group of Penicillin G (Scheme 14). Conversion of Penicillin G to 6-APA can be accomplished enzymatically in a single step [29] (and references therein), eliminat-



Scheme 15.



Scheme 16.



Scheme 17.

ing the need for protection/deprotection (Scheme 15).

2.9. *Principle 9: Catalytic reagents (as selective as possible) are superior to stoichiometric reagents*

Catalysis offers advantages over stoichiometric reactions in terms of both selectivity and energy minimization. The specificity of a catalyst favors one stereoisomer over another, one regioisomer over another, or monosubstitution over disubstitution. By driving the reaction to a preferred product, the amount of undesired by-products is decreased, thereby reducing waste generated. The amount of energy required for a given transformation is also reduced as the catalyst decreases the activation energy of the reaction.

Spivey and coworkers [30] have developed several heterogeneous catalysts for use in the condensation of acetone to methylisobutyl ketone (MIBK) (Scheme 16). Nickel on alumina, palladium zirconia, nickel and niobium, and ZSM-5 with palladium have demonstrated effectiveness, with varying degrees of conversion and selectivity, in catalyzing the condensation of acetone to MIBK. The catalytic process eliminates the stoichiometric amount of base typically utilized, as well as the formation of undesirable over-condensation products.

The high selectivity of chiral metal catalysts plays a critical role in the synthesis of the anti-inflammatory drug Naproxen (Scheme 17) [31]. The catalyst contains BINAP [2,2′-bis(diarylphospheno)-1,1′-binaphthyl], a ligand with restricted rotation due to steric factors. Naproxen is obtained in 97% yield under high pressure using the chiral metal catalyst. This class of catalyst has numerous industrial applications, particularly in the areas of pharmacy, flavor, and fragrance.

Hill and Weinstock [32] have designed polyoxometalate (POM) catalysts to selectively delignify wood. The POM catalysts are non-toxic, inorganic cluster compounds. The process uses O_2 as the oxidant and water as the solvent, eliminating the hazardous waste streams associated with paper mills. Current pulp-bleaching technology uses chlorine as the oxidizing agent, a process that produces dioxin by-products. Though not currently competitive with chlorine-based processes, POM-based technology has the potential to convert trees to paper without the use or generation of toxic chemicals.

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

Chemicals that are persistent in the environment may pose a risk to organisms due to exposure or bioaccumulation. Therefore, the fate of chemical products should be a priority in process design: will the product decompose hydrolytically or photolytically to benign substances? Is a more toxic by-product likely to be formed? Will the product biodegrade in a landfill?

The durability of polymers can present problems for wildlife and long-term disposal. As a result, attention has been focused on the design of biodegradable polymers. Natural polyhydroxyalkanoates (PHAs) are microbial polyesters that are synthesized enzymatically by bacteria. Gross and coworkers [15,33] have focused on the use of poly(ethylene glycol) in controlling the molecular weight, and, therefore, the properties, of PHAs. In addition to being biodegradable, PHA polyesters may be synthesized from renewable resources (principle 7).

An unusual application of biodegradability is in the area of road deicers. Millions of tons of sodium chloride and other inorganic salts are spread onto roadways each winter. These salts enter surface and groundwater supplies, damaging sensitive ecosystems. Salt usage during the winter months also contributes to corrosion of automobiles and deterioration of roadways. Mathews [34] uses biocatalysis to convert whey effluents into the biodegradable road deicers calcium magnesium acetate and calcium magnesium propionate. Utilization of waste biomass, generated by the dairy industry, enhances the value of these waste products, eliminates the need for treatment and disposal, and provides an economical feedstock for manufacturing alternative road deicers.

2.11. Principle 11: Analytical methodologies need to be developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances

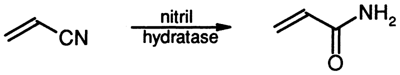
Continuous feedback is critical during the manufacturing process in order to optimize reaction conditions. In-line monitoring assists in maximizing yield and minimizing the formation of hazardous substances. Reaction conditions can be adjusted to control the generation of unwanted by-products. The use of excess reagents can be minimized by monitoring the progress of the reaction.

Subramaniam [35] uses on-line GC quantitative analysis to monitor alkylation of 1-butene/isobutane. This process replaces the traditional hydrofluoric and sulfuric acid catalysts with a solid-acid catalyst, such as HY zeolite, sulfated zirconia, or Nafion. Coke retention in the pores of the catalyst is minimized through the use of supercritical CO_2 as solvent. In-line monitoring facilitates the solid-acid catalyzed process and also satisfies principles 3 (non-toxic reagents), 5 (benign solvents), and 12 (accident prevention).

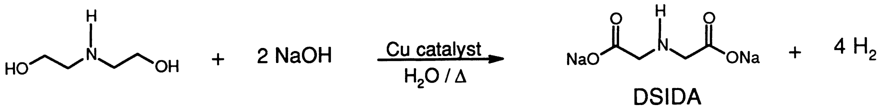
2.12. Principle 12: Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions and fires

Chemical accidents can have a devastating effect on the local community. Perhaps the most notorious chemical disaster was the accidental release of methyl isocyanate in Bhopal, India, resulting in thousands of deaths. As accidents cannot be completely prevented, it is desirable to use the most benign form of a substance available.

DuPont has developed a safer process for generating methyl isocyanate [36]. A catalytic oxidative-dehydrogenation process produces methyl isocyanate without the use of phosgene. The potential for accidental exposure is reduced by converting methyl isocyanate to the desired agrichemical product in situ.



Scheme 18.



Scheme 19.

The conventional synthesis of acrylamide employs corrosive sulfuric acid and ammonia, yielding stoichiometric quantities of ammonium sulfate along with the desired acrylamide. The same transformation can be achieved enzymatically using nitril hydratase without formation of the unwanted by-product (Scheme 18) [31]. The enzyme presents a safer and more efficient alternative to the standard reagents, and simplifies product isolation.

Disodium iminodiacetate (DSIDA) is typically synthesized via the Strecker process, using ammonia, formaldehyde, hydrogen cyanide, and hydrochloric acid. Monsanto has designed a catalytic synthesis of DSIDA, a key intermediate in the manufacture of their Roundup® herbicide [37]. The new process avoids the use of the toxic reagents present in the Strecker synthesis. Instead, it relies on the copper-catalyzed dehydrogenation of diethanolamine (Scheme 19). The product stream requires no additional purification following filtration of catalyst.

3. Conclusion

As pollution prevention moves to the forefront of environmental stewardship, chemists are increasingly utilizing all of their synthetic tools in designing safer products and processes. Approaches to green chemistry are varied: the use of benign solvents, the development of biodegradable products, and the generation of non-toxic substances all contribute to pollution prevention. Although hazardous substances and steps remain in some processes, even incremental changes make a positive contribution to pollution prevention. The central role that catalysis has played in reducing the use and generation of hazardous substances is highlighted by the wealth of examples presented here. Catalysis can be expected to remain a cornerstone in building a sustainable chemical community through green chemistry.

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