聲明

本檔案之內容僅供下載人自學或推廣化學教育之非營利目的使用。並請於使用時註明出處。[如本頁取材自〇〇〇教授演講內容]。

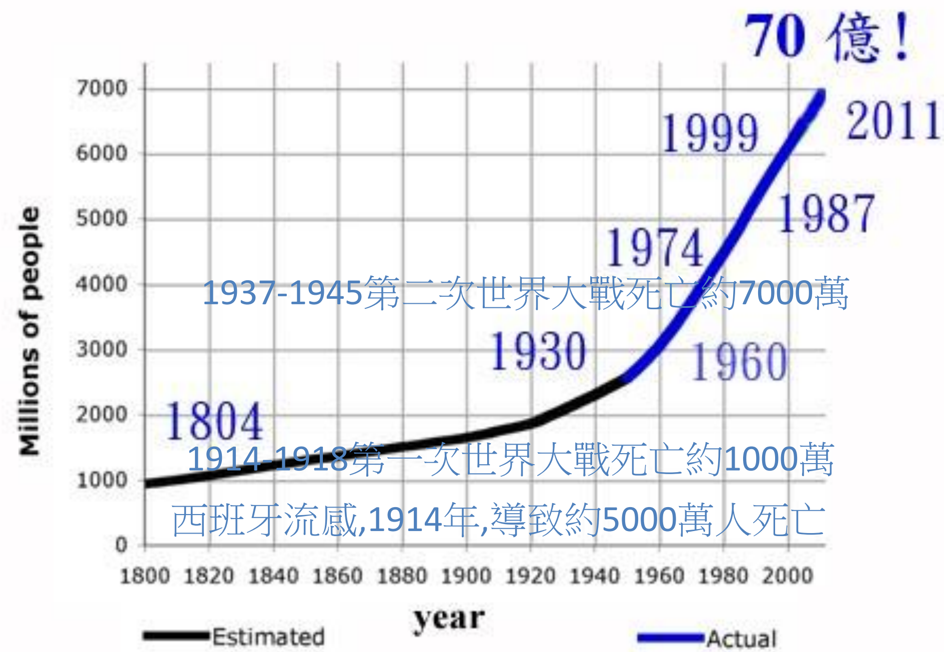
慈濟東華兩校三系學術交流研討會
Dong Hwa and Tzu-chi University Mini-Symposium
Advances in Biomedical Research and Biocontrol

Green chemistry - a key to balance economic development and environmental protection
綠色化學-經濟發展與環境保護共生之關鍵

2013年5月3日 2:10 – 3:10

甘魯生 教授 lskan@gate.sinica.edu.tw
中央研究院化學所兼任研究員
國科會化學中心永續/綠色化學通訊 編輯 (2011)
大同大學生物工程學系綠能及綠色化學月刊 顧問 (2010-2011)
大同大學 講座教授 (2008 -2010)
綠色/永續化學工作坊講員 (2010-)
財團法人傑出人才基金會傑出人才講座

Civil Engineering Field leveling, terracing, irrigation ditches
Mechanical Engineering Plows, tractors, a tool for every task
Chemical Engineering
Gasoline and other fuels
Fertilizers, pesticides
Nylon, rayon, polyester, and other synthetic materials
Plastics
Antibiotics and other medicines
Water purification

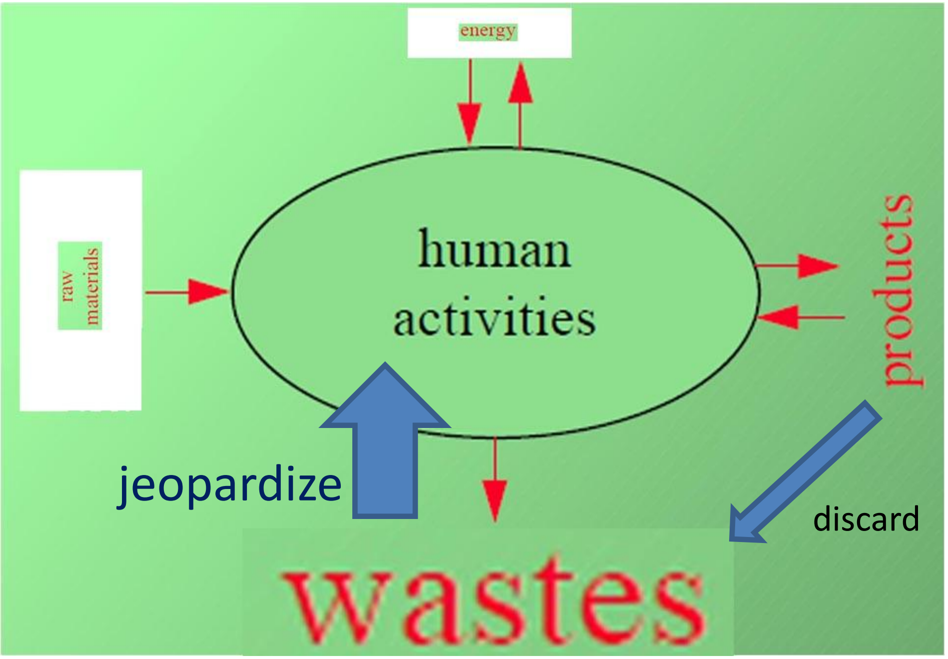


傳染病: 鼠疫、西班牙流感、日本腦炎、霍亂 、退伍軍人症、瘧疾、狂牛症
戰爭
飢饉

Canica May Camacho 全世界象徵性第70億人口
2011年10月31日出生於菲律賓馬尼拉
(Erik De Castro/AFP/Getty Images)
(http://www.guardian.co.uk/world/2011/oct/31/seven-billionth-baby-born-philippines?intcmp=122)

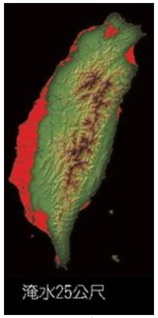
現在人口數
http://ngm.nationalgeographic.com/7-billion

Wastes (solid, liquid, gas, emission)



• Pesticides: DDT, Aldrin, Chlordane, Dieldrin, Endrin, Heptachlor, Mirex, Toxaphene
• Industrial by-products: Dioxin and chlorinated benzofurans
• Pesticide and industrial by-product: Hexachlorobenzene (HCB)
• Industrial chemicals: Polychlorinated biphenyls (PCB)

Cuyahoga River- 1972 Clean Water Act
Love Canal- 1980 Comprehensive Environmental Response, Compensation & Liability Act, better known as Superfund. Emergency Planning & Community Right-to-Know Act, requires that industries report toxic releases



Environment Impact
Depletion of ozone layer (The Montreal Protocol, 1989)
Greenhouse Gases (GHG) and Climate Changes. The issue of Global Warming. (The Kyoto Protocol, 1996; Doha climate change conference, 2012)
Bio-accumulation of persistent pollutants. The case of DDT.(The Stockholm Convention, 2001)

永續(綠色)化學大事紀

自Rachel Carson所著之『寂靜的春天』一書出版之後的1970年代引起「環保議題」的熱烈討論.

1972 聯合國環境委員會在瑞典Stockholm召開『人類與環境會議』.揭櫫了人類要和環境良性互動.並訂每年六月五為『世界環境日』.

1977 聯合國教科文組織(UNESCO)強調環境教育的倫理價值觀,成為永續發展的籃圖(Tbilisi宣言).

1980 『世界自然保育方略(World Conservation Strategy)』一書出版.此書由聯合國環境計畫組織、世界保育聯盟和野生動物保育協會共同撰文.其目的為達成資源保護以供永續開發.

1986年美國國會通過了『應急規劃和社區知情權法案(Emergency Planning and Community Right-to-Know,或EPCRA)』.這是美國有害化學物質清除的超級基金(superfund)修正案之一.它授權給州及地方政府有被告知及取得有害化學物質之權利以及有權作出對化學有害物質應對方案.這啟發了民眾對有害化學物質的認識和落實了環境保護的意識.

1987 聯合國環境委員會(由挪威首相 Brundtland為召集人) 提出永續發展 Sustainable Development 的理念『我們共同的未來』(Our Common Future).強調『滿足這一代的需求,但不以下一代滿足他們自身需求的能力作為妥協 (Meeting the needs of the present generation without compromising the ability of future generations to meet their own needs)』.此宣言將人類福祉相關的因素列入考慮,打破了以往經濟發展(economic development)與環境保護(environmental protection)對立的局面,成為永續化學發展的策略和目標.

同年 我國行政院成立環境保護署推動自然環境保護,自然生態保育及合理運用資源等.

1990 美國訂定污染防治法案 (The Pollution Prevention Act),提倡「源頭減廢勝於管末處理」政策.

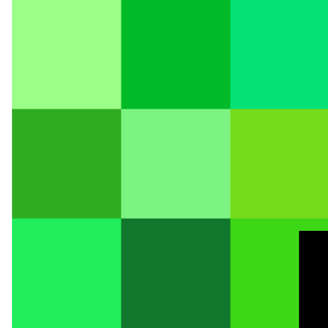
同年 美國環境保護署推行永續化學.

1991 Paul T. Anastas博士(時任職美國環境保護署Environmental Protection Agency, EPA) 首次提出『綠色化學(Green Chemistry Program)』一詞將永續化學口語化並定義為:『發明、設計和利用化學產品與化學製程,以減少或消除有害物質之使用與生產』.此名詞沿用至今.

1992『地球高峰會議』於巴西里約熱內盧召開,制定了里約宣言、二十一世紀議程、氣候變化綱要公約、生物多樣性公約及森林宣言等五項公約.
1995 美國成立『美國總統綠色化學挑戰獎 (The Presidential Green Chemistry Challenge Awards)』致力推行綠色化學.
1997 全球綠色化學運動先驅Joseph Breen創立美國綠色化學研究所(GCI)並出任第一屆所長.2001年合併入美國化學會(American Chemical Society).
1998 京都議定書.制定二氧化碳排放目標.由於只對已開發國家限制(中國、印度列開發中國家),以至有些工業大國(美國及澳大利亞)未簽署.
同年 Paul T. Anastas 博士和John C. Warner 博士合著“Green Chemistry: Theory and Practice”一書由Oxford University Press出版.此書提出綠色化學的十二原則.成為落實綠色/永續化學之指標。
1999 英國皇家化學學會成立『綠色化學網』(The Green Chemistry Network)並出版綠色化學學誌(Green Chemistry, IF=6.32)).
2000 日本推動綠色和永續化學.
2001 國際純粹與應用化學組織(IUPAC)成立綠色化學委員會.
此後世界各國政府機關、學術界順應發展趨勢開始響應綠色/永續化學之研究,並著手推動與實行、設立研究組織、舉行研討會來致力推行綠色/永續化學.
我國國科會化學中心於2006年成立永續/綠色化學網路資源共享網(網址:http://gc.chem.sinica.edu.tw/).
各大學亦設立綠色化學課程.2010年成立綠色化學種子教師培訓工作坊,講師有趙奕姼、劉廣定、廖俊臣、周德璋、甘魯生五位.2012年有許拱北、蔡蘊明、陳月枝、沙晋康等老師加入.

What is green chemistry?
什麼是綠色(永續)化學?

- Green chemistry is the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances.
- **發明、設計化學產品及其製造過程不涉及或不產生有害物質的化學都可統稱為永續化學. 由於無害可以永續經營.**
- Discovery and application of new chemistry/technology leading to prevention/reduction of environmental, health and safety impacts at source
- **探索並應用致使能防止/減少對環境、健康及安全衝擊之源頭的新化學及技術.**


520-580 nm


綠色化學=永續化學

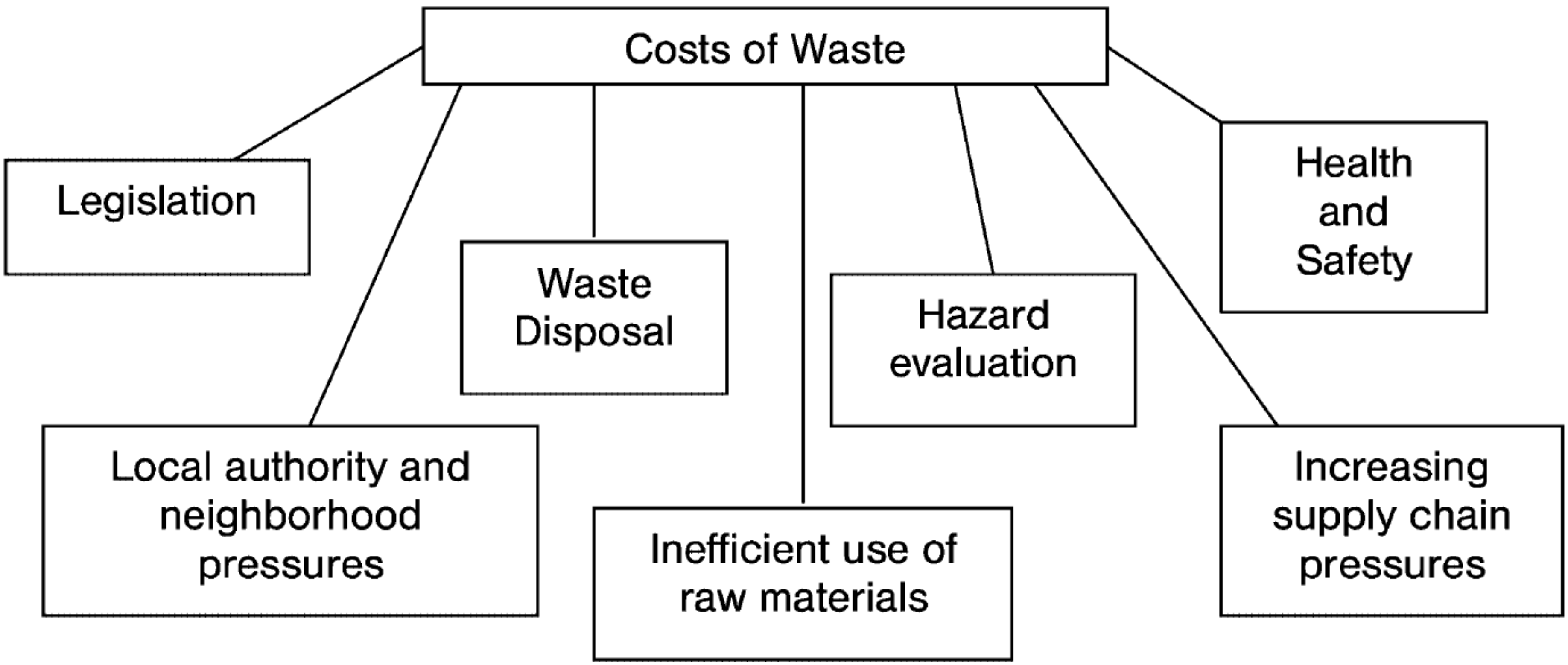
P. Tundo, P. Anastas, D. Black, J, Breen, T, Collins, S, Memoli, J, Miyamoto, M, Polyakoff, and W, Tumas, Synthetic pathways and processes in green chemistry. Introductory overview, *Pure and Applied Chemistry, 2000, 72, 1207-1208*

永續(綠色)化學十二項原則

Paul Anastas and John Warner in Green Chemistry: Theory and Practice (Oxford University Press: New York, 1998).

1. **Prevent waste**: It is better to prevent waste than to treat or clean up waste after it is formed.
避免廢料：設計化學合成,使之避免廢料,不產生需處理或清理的廢料.

Cost of waste



環境因子(environmental factor): 反應後產物和反應中所有廢物之比.廢物包括了副產物及溶劑、催化劑、補助劑等.

環境因子(E) = 廢物的總量(公斤)/產物的重量(公斤)

Industry	E-factor	Annual Production tonnage
Oil Refining	*ca*. 0.1	10^6 - 10^8
Bulk Chemicals	<1 to 5	10^4 - 10^6
Fine Chemicals	5 to >50	10^2 - 10^4
Pharmaceuticals	25 to >100	10 – 10^3

R. A. Sheldon, *Chem. Ind.*, **1997**, 12 – 15.

E-Factor = Total mass of materials required to produce 1kg product (mass intensity) – 1.

製程質量強度 (Process Mass Intensity, PMI)

A key, high-level metric for evaluating and benchmarking progress towards more sustainable manufacturing, has chosen by American Chemical Society Green Chemistry Institute's Pharmaceutical Roundtable.

PMI=total mass in a process or process step (kg)/mass of product (kg)

= E + 1

C. Jimenez-Gonzalez, C. S. Ponder, Q. B. Broxterman, and J. B. Manley, "Using the Right Green Yardstick: Why Process Mass Intensity Is Used in the Pharmaceutical Industry To Drive More Sustainable Processes", Org. Process Res. Dev. 2011, 15, 912–917. (dx.doi.org/10.1021/op200097d)

考慮廢物性質

E = **S** (廢料總量/產物總量*) (*都以公斤計)

S(嚴重性因子) = 1 – 200, 依廢料之性質及多寡而定

Hazardous Waste to Land Disposal/Containment	10
Hazardous Waste to Incineration	4
Non-Hazardous Waste to Landfill	2
Waste Water (to Treatment Plant)	0.5

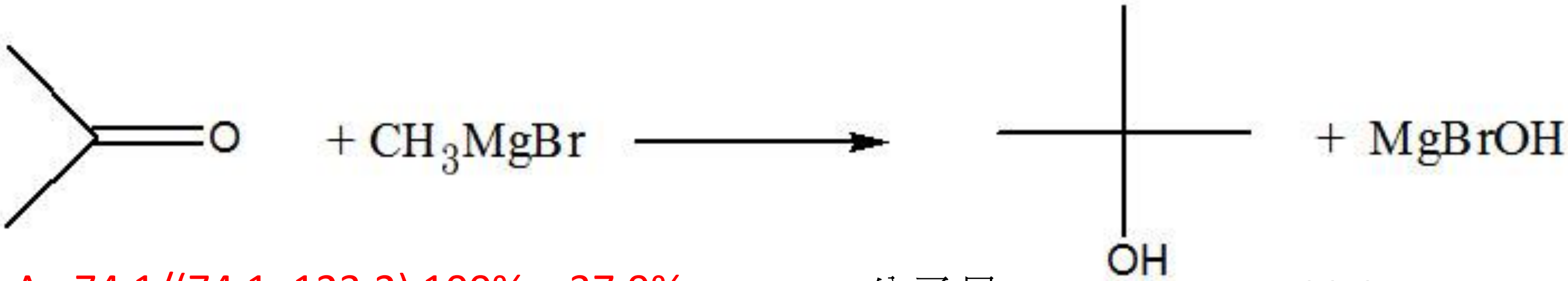
Roger A. Sheldon, Chem & Ind., 7-Dec-1992, pg. 903
Roger A. Sheldon, Chem. Commun., 2008, 3352-3365

2. **Atom economy**: Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

發揮最大的原子經濟: 設計合成使得終極產物含有最大部分的原始反應料. 而沒有甚麼浪費的原子. 即便有也是很少.

原子經濟 (A): (主產物/全部產物) x 100%

B. M.Trost, *Science, 254, 1471,* ***1991;*** *Acc. Chem. Res. 35, 695,* ***2002.***



A =74.1/(74.1+123.2) 100% = 37.9%

分子量=74.1 123.2

原子經濟(atom economy) = 100%

加成反應: 例: 水加氧氣生產雙氧水.化學反應式為 $2H_2O + O_2 \rightarrow 2H_2O_2$

重組反應: 例: 氫原子轉移(hydride shift).化學反應式為

$CH_3CH(CH_3)CH{=}CH_2 \rightarrow CH_3CH{=}CHCH_2CH_3$

原子經濟 < 100%

取代反應: 例: 甲烷和氯氣作用產生氯化甲烷. $CH_4 + Cl_2 \rightarrow CH_3Cl + HCl$

欲得到的產物質量 = (12+3x1)+35.5 = 50.5; 反應物的總質量 = (12+4x1)+2x(35.5) = 87

原子經濟(%) = 100% x 50.5/87 = 58%

分解反應: 例: $Ca(OH)_2 \rightarrow CaO + H_2O$

欲得到的產物(CaO)質量 = 40.1+16 = 56.1; 反應物的總質量 = 40.1+2x(16+1) = 74.1

原子經濟(%) = 100% x 56.1/74.1 = 76%

其它反應的化學通式為 $aA + bB \rightarrow cC + dD$

若欲得到的產物是眾產物之一,照上列的計算可知原子經濟小於100%.

3. **Less Hazardous Chemical Syntheses**: Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

低危險的化學合成: 無論在何地,只要實際可行,設計化學合成方法應優先考慮人類健康和環境,所用的原料及製出的成品都是無毒的或毒性很低的.

4. **Designing Safer Chemicals**: Chemical products should be designed to effect their desired function while minimizing their toxicity.

設計更安全的化合物: 化學產品應被設計成能在它們的毒性縮到最小下實現它們所賦與的功能.

毒性度量

環境危險評估以環境中的預測濃度(**P**redicted **E**nvironmental **C**oncentration)和不傷害環境之預測濃度(**P**redicted **N**o **E**ffect **C**oncentration)之比為度量:

險商(risk quotient) = PEC/PNEC

(http://www.scienceinthebox.com/en_UK/safety/riskassenv_en.html)

RQ (tributyltin oxide) vs 4,5-dichloro-2-*n*-octyl-4-isothiazolin-3-one (Sea-Nine™) = 15-430 vs 0.024 – 0.36

D. K. Larsen, I. Wagner, K. Gustavson, V. E. Forbes, T. Lund, Long-term effect of Sea-Nine on natural coastal phytoplankton communities assessed by pollution induced community tolerance, Aquatic Toxicology 62 (2003) 35/44

Presidential Green Chemistry Challenge Award: http://www.epa.gov/gcc/pubs/pgcc/presgcc.html

風險 = f(危險程度 x 曝露時間)

毒性度量方法: ID_{50}

評估方法

瞭解物理與化學性質; 估量在環境釋放的程度; 在環境中消長情形; 危險評估.(危險評估是要不斷的做)

(http://www.scienceinthebox.com/en_UK/safety/riskassenvapproach_en.html)

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

更安全的溶劑和輔助劑: 有關(化學合成)的輔助物質(即: 溶劑、分離劑等),以不用為原則,若要用,也選擇無害或為害低的為好.

Criteria and data points for scoring

- Safety
  - NFPA rating
  - Flammability
  - Auto Ignition temperature
  - Boiling point
  - Flash point
  - Conductivity (static risk)
  - Peroxide formation
- Health
  - Reprotoxic, carcinogenic and mutagenic effects
  - Toxicity
  - Skin effects
  - Sensitisation
  - Occupational Exposure Limit values
  - Vapour pressure

NFPA: National Fire Protection Association

- Environment (Air impact)
  - Volatility
  - Odour
  - Photochemical Ozone Creation (POCP) potential
  - Photolysis
  - Ozone Depletion Potential (ODP)
  - Global Warming Potential (GWP)
- Environment (Water impact)
  - Persistence (Biodegradation)
  - Bioaccumulation (LogPow)
  - Ecotoxicity
  - Water solubility
- Environment (Waste)
  - Potential for incineration (degree of halogenation, heat of combustion)
  - Potential for recycle (boiling point, miscibility with water, number of close boiling solvents, ease of drying, azeotrope formation)

A. D. Curzons, D. C. Constable, and V. L. Cunningham, Clean Products and Processes, (1999), 1, 82-90

溶劑強度(solvent intensity, SI) = 溶劑總量(公斤)/產物總量(公斤)

Finding a sufficient range of green solvents

Preferred	Usable	Undesirable
Water	Cyclohexane	Pentane
Acetone	Toluene	Hexane(s)
Ethanol	Methylcyclohexane	Di-isopropyl ether
2-Propanol	TBME	Diethyl ether
1-Propanol	Isooctane	Dichloromethane
Heptane	Acetonitrile	Dichloroethane
Ethyl Acetate	2-MeTHF	Chloroform
Isopropyl acetate	THF	NMP
Methanol	Xylenes	DMF
MEK	DMSO	Pyridine
1-Butanol	Acetic Acid	DMAc
t-Butanol	Ethylene Glycol	Dioxane
		Dimethoxyethane
		Benzene
		Carbon Tetrachloride

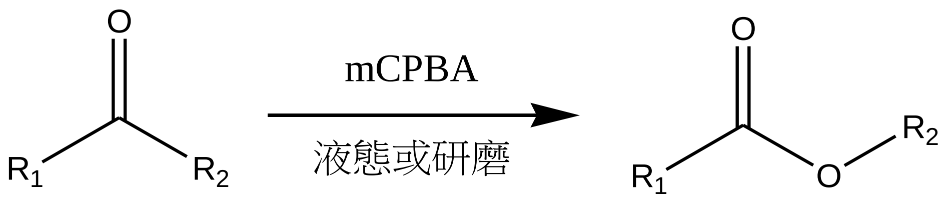
Fig. 5 Solvent selection guide.[18]

Organic Process Research & Development 2011 IF: 2.391; Citation: 3.609
Editor-in-Chief: Trevor Laire
http://pubs.acs.org/journal/oprdfk
Published: January 5, 2012 by Trevor Laire
"The journal encourages researchers to consider the environmental consequences of the way in which they perform their experiments and to minimize waste." and
"From 2012 the policy on use of organic solvents has been changed to discourage scientists from using particular solvents and to encourage them to seek alternatives wherever possible; papers containing strongly undesirable solvents (e.g., benzene, carbon tetrachloride, chloroform, HMPA, carbon disulfide, etc.) will only be considered if accompanied by an analysis of alternatives or if a convincing justification for such use is presented."

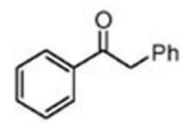
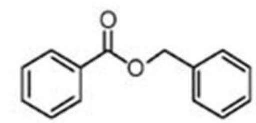
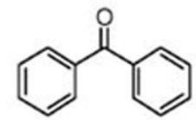
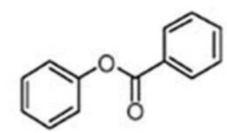
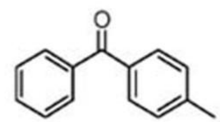
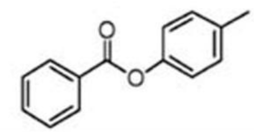
ChemSusChem IF: 6.827
Editorial by G. M. Kemeling (Editor-in-chief), ChemSusChem 2012, 5, 2291 – 2292
Specifically, we ask of our authors the following:
* to avoid, if possible, the use of harmful solvents and replace these with less-harmful alternatives;
* to rationalize the choice of solvent in manuscripts.
We ask of referees:
* to closely scrutinize the use of solvents as described in the Results and Discussion and Experimental paragraphs;
* to ask for clarification and justification in case the choice of solvent is not commented on.

無溶劑 > 水 > 超臨界溶劑 > 離子溶液 > 揮發性有機溶劑 (>為優於之意)

無溶劑 實例: Baeyer–Villiger 氧化反應(亦稱之Baeyer – Villiger重組反應)
Baeyer–Villiger 氧化反應是酮化合物和過氧酸作用產生酸或酯化合物.其通式如下:



R_1和R_2分別是有機功能基,mCPBA是*meta*-chloroperoxybenzoic acid的縮寫,是一間氯苯過氧酸.也可用過氧醋酸和五氟過氧醋酸為氧化物(註十二).
下表是總結幾個Baeyer–Villiger 氧化反應在溶液中或研磨反應之結果.

反應物	反應時間 (小時)	產物	產率(%) 研磨	產率(%) 溶劑氯仿
	24		97	46
	24		85	13
	24		50	12

Water in organic reaction
回顧論文(1) Li, C.-J., “Organic Reactions in Aqueous Media with a Focus on Carbon-Carbon Bond Formation”, Chem. Rev., (1999), 93, 2023-2035; (2) Li, C.-J., “Organic Reactions in Aqueous Media with a Focus on Carbon-Carbon Bond Formations: A Decade Update”, Chem Rev., (2005), 105, 3095-3165.
書 (1) Li, C.-J., “Organic Reactions in Aqueous Solution”, John Wiley, 1997. (2) Li, C.-J., Chan, T.-H., “Comprehensive Organic Reactions in Aqueous Media”, 2nd ed., Wiley-Interscience, 2007.

Supercritical carbon dioxide fluid, critical pressure (31.1 atm), temperature (73.8 C)
non-toxic, non-flammable, inexpensive, environmentally benign
solvating power similar to hexane and CCl_4. extraction decaffeinated coffee.

Replace perchloroethylene (perc) in dry clean
NoDryClean (http://www.nodryclean.com/carbon_dioxide_cleaning.htm)

Examples of catalytic reactions in supercritical fluids

Type of reaction	Reaction	Catalyst	Reaction conditions	Effect
Alkylation	Isobutane + isobutene	H–Y (dealuminated)	Solvent: isobutane, $T = 50–140\,°C$, $P = 3–5\,MPa$	Increase activity, increase lifetime
Esterification	Oleicacid + methanol	Ion-exchange resins	Solvent: CO_2, $T = 40–60\,°C$, $P = 0.9–1.3\,MPa$	Increase activity
Hydrogenation	Fats and oil	Supported Pd	Solvent: propane, $T = 50–100\,°C$, $P = 7–12\,MPa$	Increase activity, increase selectivity
Isomerization	1-Hexene	Supported Pt	Solvent: CO_2 (cosolvent: pentane), $T = 250\,°C$, $P = 18\,MPa$	Increase activity, selectivity and lifetime
Oxidation	Toluene to benzaldehyde	Co/alumina	Solvent: CO_2, $T = 100–200\,°C$, $P = 8\,MPa$	Increase selectivity

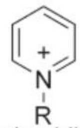
A. Baiker, Chem. Rev. 99 (1999) 453.

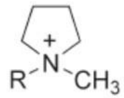
Extracted d-limonene from orange peel. L.C. MacKenzie, et al., *Green Chem.*, ***2004, 6, 355-358.***

Ionic liquid

Cations


1-alkyl-3-methylimidazolium


1-alkylpyridimium


1-alkyl-1-methylpyrrolidinium

R_4N^+

tetraalkylammonium

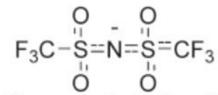
R_4P^+

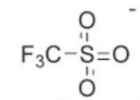
tetraalkylphosphonium

R_3S^+

trialkylsulfonium

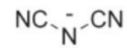
Anions


bis(trifluoromethylsufonyl)imide
$[NTf_2]^-$

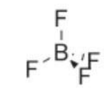

trifluoromethanesulfonate
triflate, $[OTf]^-$

RSO_4^-

alkylsulfate
$[C_nSO_4]^-$


dicyanamide
$[N(CN)_2]^-$


hexafluorophosphate
$[PF_6]^-$


tetrafluoroborate
$[BF_4]^-$

- air stable
- no measurable vapor pressure (non volatile)
- lack of flammability
- high conductivity
- high thermal and chemical stability for wide temperature range by fine tuning the variation of cations or anions
- recycling of ionic liquids for re-use was possible without decrease in yield--environmentally friendly

http://ilthermo.boulder.nist.gov/ILThermo/

(1) Olivier-Bourbigou, H.; Magna, L.; Morvan, D. Appl. Catal., A (2010), 373, 1. (2) Parvulescu, V. I.; Hardacre, C. Chem. Rev. (2007), 107, 2615. (3) Welton, T. Coord. Chem. Rev. (2004), 248, 2459. (4) Dupont, J.; de Souza, R. F.; Suarez, P. A. Z. Chem. Rev. (2002), 102, 3667, and (5) Wasserscheid, P.; Keim, W. Angew. Chem., Int. Ed. 2000, 39, 3772; (6) Jason P. Hallett and Tom Welton, Chem Rev. (2011), 11, 3508-3576.

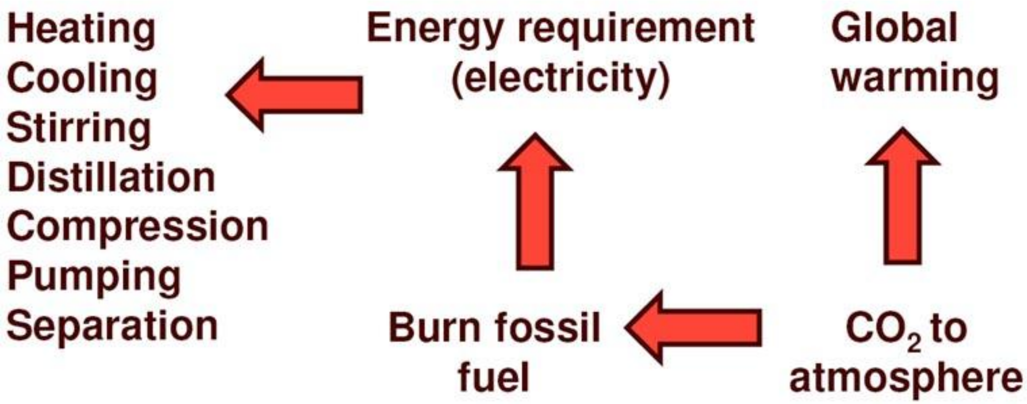
6. **Design for Energy Efficiency**: Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.

為用能效率而設計: 化學過程中對能量的需求應該要將其對環境和經濟的衝擊縮為最小.如果可能, 合成方法應該在常溫和常壓下進行.

耗能指數: 溫度

5 (反應溫度低於-20° C或高於280° C)
3 (反應溫度0 - -20° C或160 - 280° C)
2 (反應溫度0 - 10° C或90 - 160° C)
1 (反應溫度10 - 20° C或30 - 90° C)
0 (反應溫度20 - 30° C)

壓力



Step EE (Energy Efficiency) = $$\frac{(f_T+|1\text{-}Pressure(atm)|)*time\ (hrs)*Weight*Heat\ Capacity\ (J/gm\cdot{}^{\circ}K)}{Wt\ Desired\ Product}$$

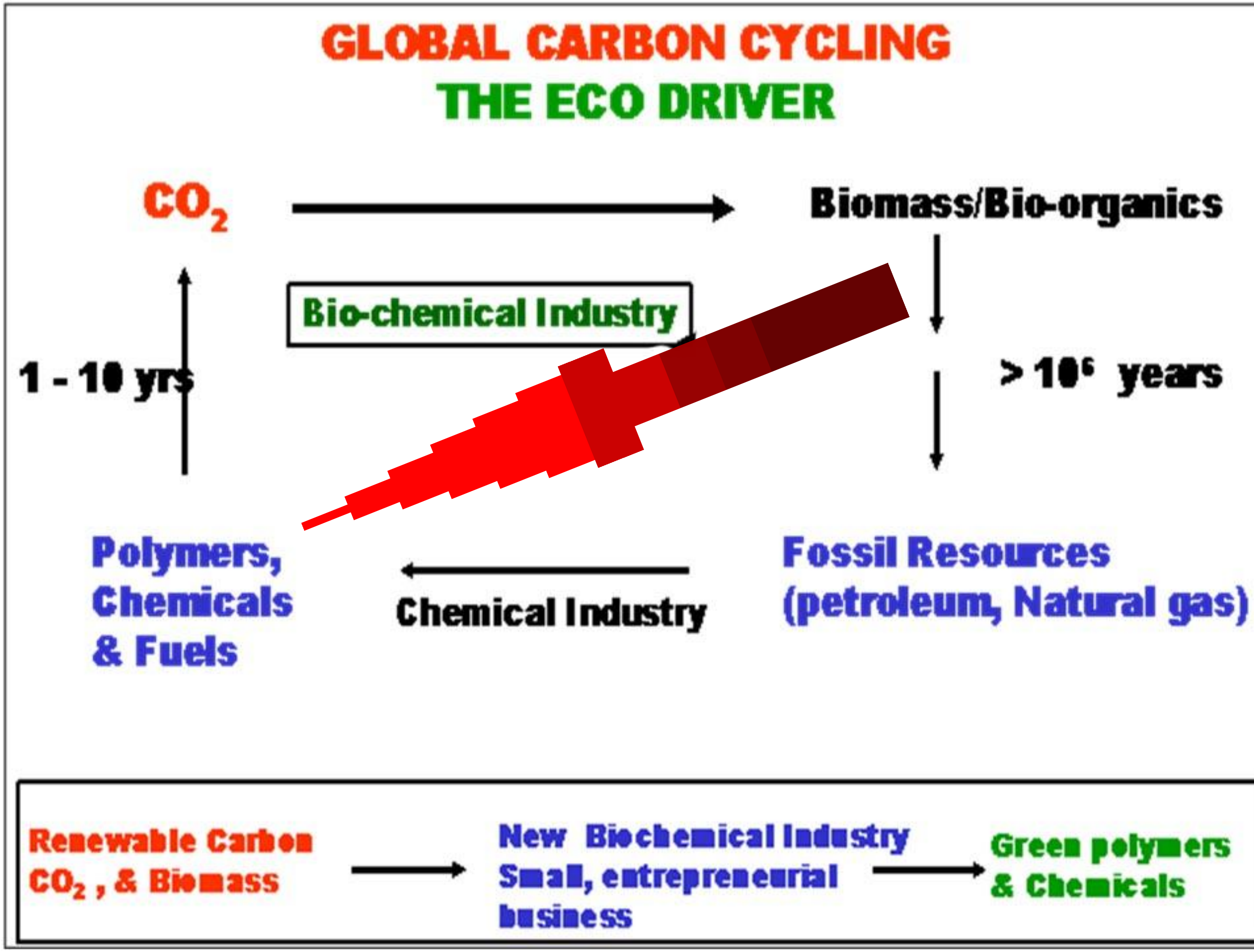
減少能量 (非傳統方法)

Microwave heating
Photochemistry
Sonochemistry
Electrochemistry
Mechanochemistry
Flash chemistry
Catalytic chemistry (#9)

綠色/永續化學網路資共享網
http://gc.chem.sinica.edu.tw/
綠色/永續合成化學工作坊
http://gc.chem.sinica.edu.tw/workshop/notes.php
綠色/永續化學網路資共享網通訊
http://gc.chem.sinica.edu.tw/learn.html

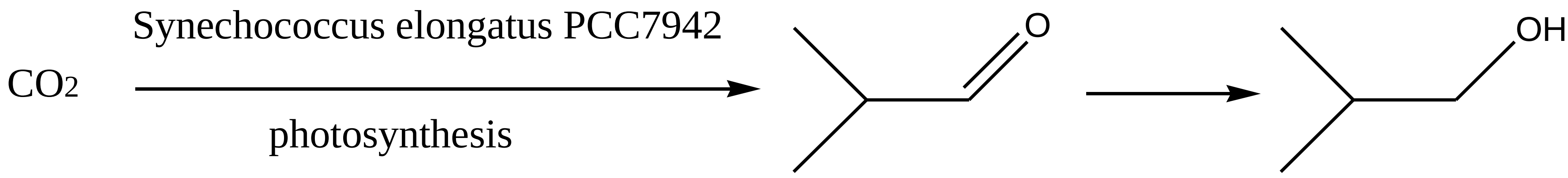
7. **Use of Renewable Feedstocks**: A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

使用可再生的原料: 祗要技術和經濟行得通時,儘量用再生而非消耗的生物料和原料.



Modified from http://www.worldofteaching.com/

微生物行光合作用由葡萄糖生產異丁醛(isobutylaldehyde)



isobutyraldehyde　　isobutanol

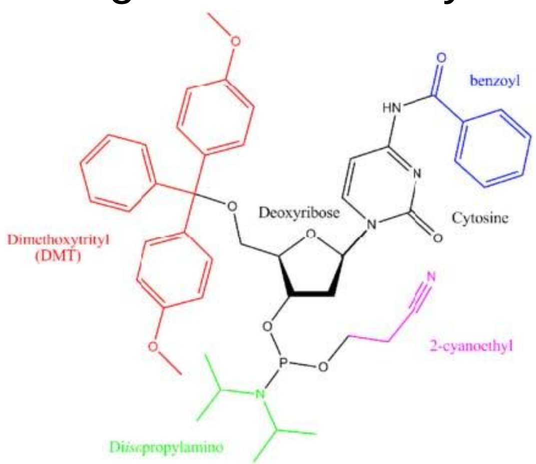
生質能	微生物	產率(微克/升.小時)
氫氣	Anabaena variabilis PK84	1,000
	Anabaena variabilis AVM13	900
	Chlamydomonas reinhardtii31	800
	Oscillatoria sp. Miami BG7	400
乙醇	S. elongatus	150
異丁醇	S. elongatus	3200
異丁醛	藻類	3500
	基因改良S. elongatus	6200

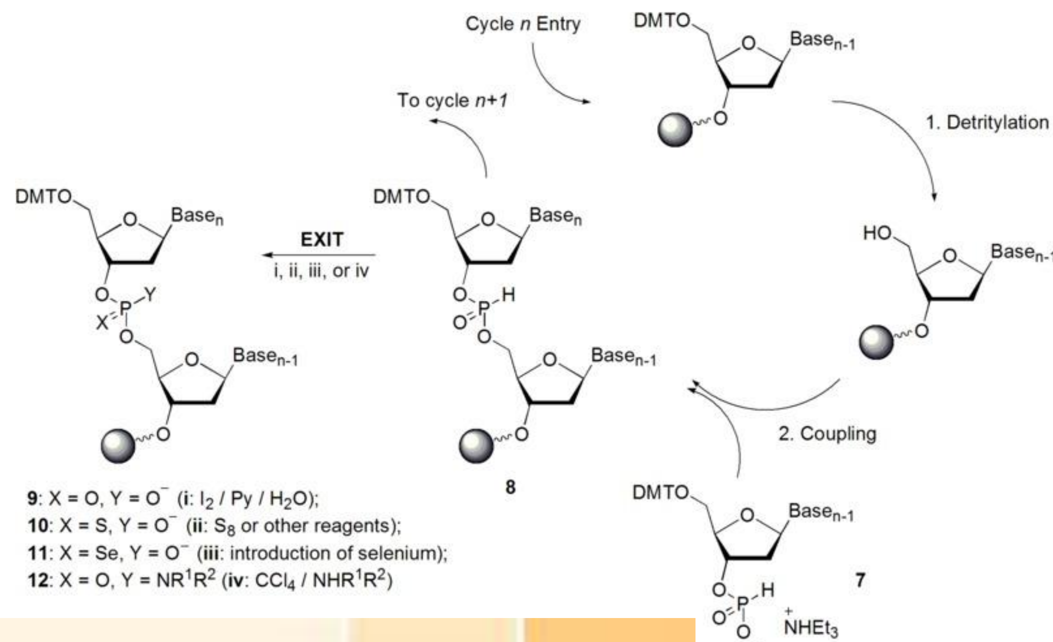
Atsumi, S., Hanai, T. & Liao, J.C. Non-fermentative pathways for synthesis of branched-chain higher alcohols as biofuels. Nature (2008) 451, 86–89.
S. Atsumi, W. Higashide, and J. C. Liao, Direct photosynthetic recycling of carbon dioxide to isobutyraldehyde, *Nature Biotechnology*, (2009) **27**, 1177 – 1180.
http://www.nature.com/nbt/journal/v27/n12/pdf/nbt.1586.pdf
美國總統綠色化學獎http://www.epa.gov/greenchemistry/pubs/pgcc/winners/aa10.html

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

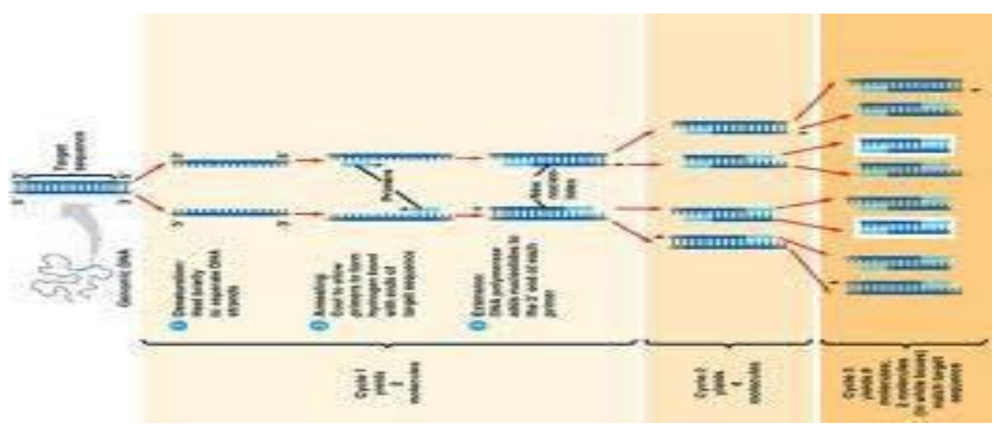
減少衍生物: 儘可能減少或避免不需要的衍生物(阻擋基、保護物/去保護物、物理/化學過程中之暫時修飾等),因為此步驟需額外的試劑且產生廢料.

DNA/RNA oligonucleotides synthesis





Polymerase chain reaction

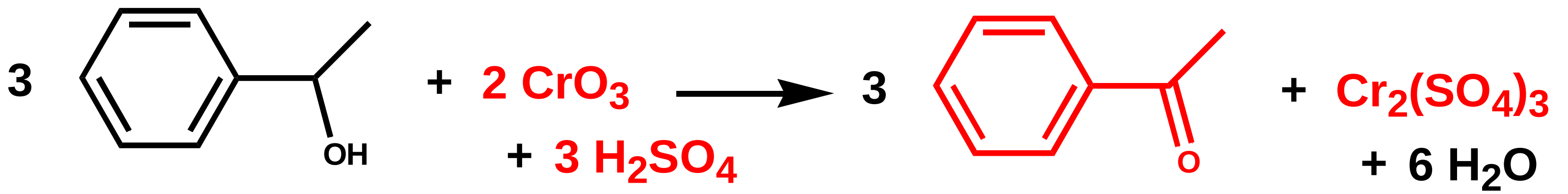


9. **Catalysis**: Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

催化作用: 儘可能用有選擇能力之催化劑優於化學當量的試劑.

Commercial Synthesis of Acetophenone

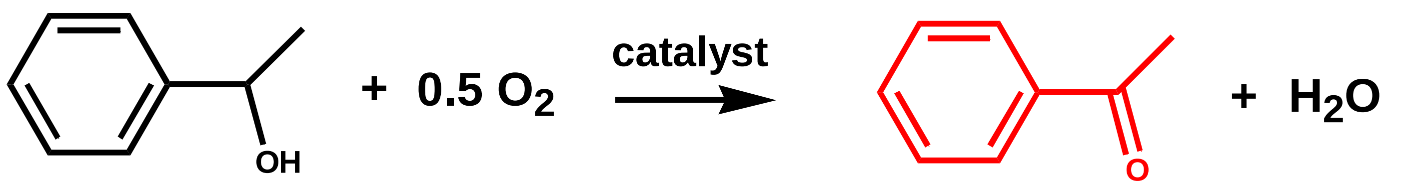
Time-Honored Synthesis of Acetophenone(a TRI chemical):



Phenethyl alcohol **Acetophenone**

overall synthesis efficiency only 42 %

"Green Chemistry" Synthesis of Acetophenone:



Phenethyl alcohol **Acetophenone**

overall synthesis efficiency = 87 % !!

構成綠色(永續)催化劑的條件有(1)效率高;(2)能回收;(3)可被生物分解;(4)無毒性;(5)由能再生的來源製造;(6)能將毒物降解成無毒或毒性低之物質

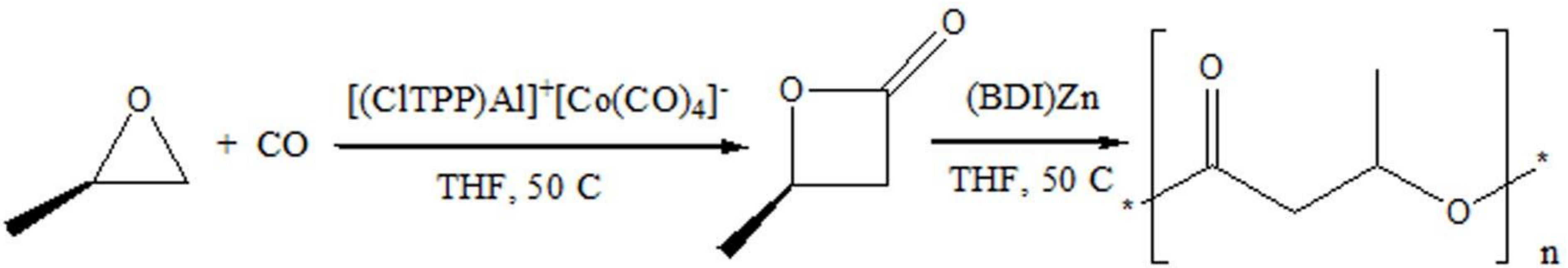
生物催化劑(酵素)符合性是相當高的.因為它(1)自然發生,無毒性;(2)反應溫和並省能;(3)溶於水;(4)效率高;(5)立體結構的選擇性及(6)一鍋(one-pot)反應

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.

為分解而設計: 化學產物應被設計成當它們的功能結束時能分解為無害的降解物而不會存留在環境中.

環境友善指數(化合物的半生命期): *5 (以小時計); 4 (以天計); 3(以週計); 2(以月計); 1(以年計)*

Synthesis of (poly(3-hydoxylbutyrate) (P3HB)

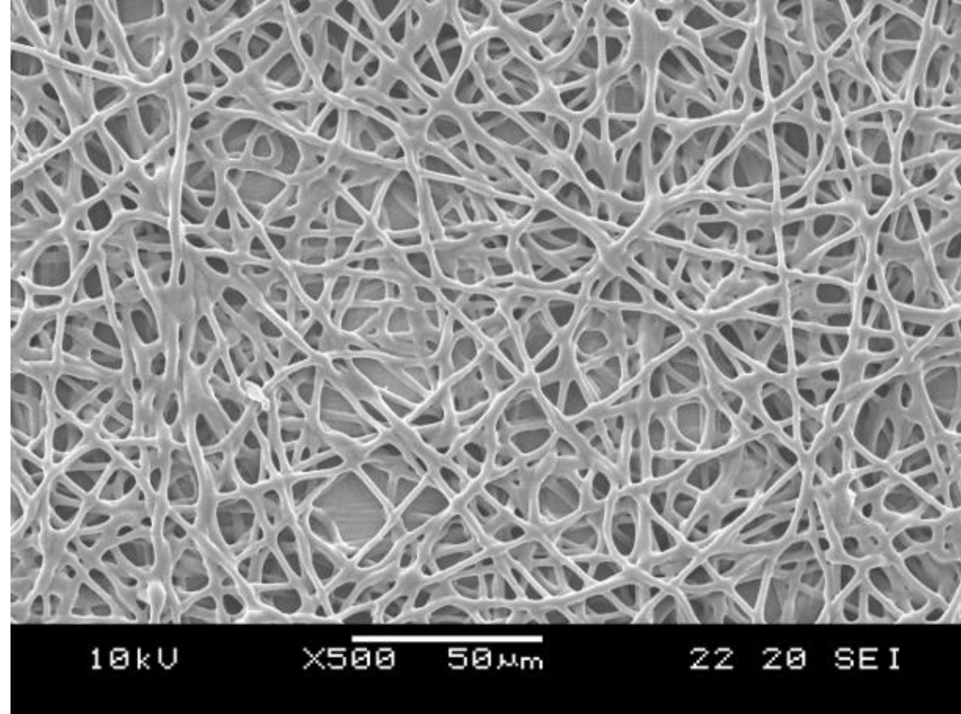


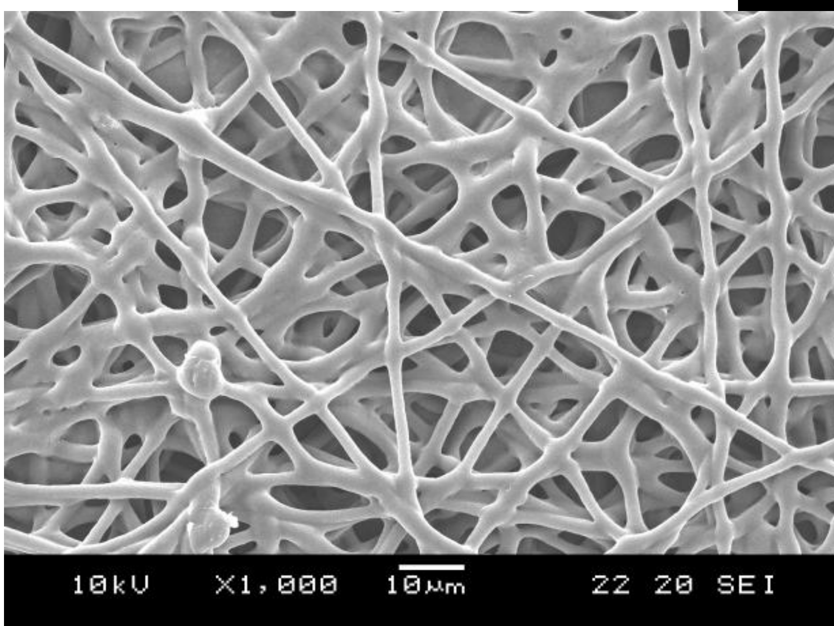
Erin W. Dunn and Geoffrey W. Coates, Carbonylative Polymerization of Propylene Oxide: A Multicatalytic Approach to the Synthesis of Poly(3-Hydroxybutyrate), J. AM. CHEM. SOC. 2010, *132*, 11412–11413

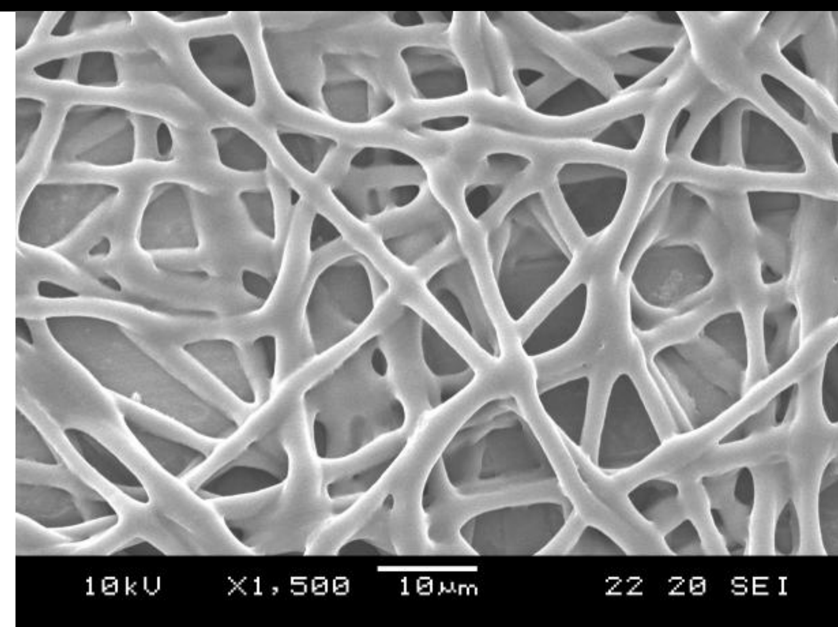
(2012)年美國綠色化學總統獎之學術獎

http://www.epa.gov/greenchemistry/pubs/pgcc/winners/sba05.html

高細密度PHA
(Polyhydroxyalkanoates)
電紡絲薄膜製品







大同大學生工系陳志成教授提供

生命循環分析(Life Cycle Analysis,簡稱LCA)

定義: 這裡所謂之生命是指人類所生產物品的過程.生命循環分析的定義是估算一件物品由其製造的採集原料開始,經過製造、運輸、被利用(製造此物品之目的)後的去處(回收再利用、掩埋、焚燒等)整個過程對環境可能的沖擊.

簡言之是要徹底瞭解一件物品從『無』到『有』再到『無』的過程,而不光是我們享受它『有』的這一段.LCA還有許多別的稱呼如生命循環盤點(Life Cycle Inventory)、生命循環估算(Life Cycle Assessment)、從搖籃到墳墓分析(Cradle to Grave Analysis)、生態平衡分析(Eco-balancing)、塵歸塵的需能量(Dust-to-dust Energy Cost)以及物質流動分析(Material Flow Analysis)等.

分析項目: 要分析物品生命中能產生多少能使地球溫度上昇的溫室氣體(二氧化碳、甲烷、氧化氮等)、 使水源及土壤酸化物質(硫化物)、能引起呼吸道疾病塵埃(一氧化氮)、能使臭氧層稀薄的物質(冷凍劑)、能使湖泊優氧化物質(磷化物)、生態毒和有毒之污染物、使耕地沙漠化的物質以及能利用之土地和石化燃料枯竭等.

研究方法: 先界定估算的目標和範疇.這一點至為重要,尤其是範疇.因為可導至完全不同的結果.其次將輸入之原料及能和輸出的產品,副產品,廢物列表.也要將特定物質的應用和釋出的詳盡列表.之後評估對環境沖擊的結果.

可達成目標: 完成物品的LCA之後有助瞭解此物品對環境污染程度,有助於減少污染.瞭解生產此物品用能量,有助於節省不能再生之資源.應用前二項數據可進一步發展和利用更綠色之科技使回收、再利用極大化和應用最適當和最先進之污染防制技術來保護生態系統.

效益: 做好LCA對製造者而言也是有利的,利用LCA數據可發展和改良產品,可降低成本,爭取『環境標籤』後可增加競爭力.

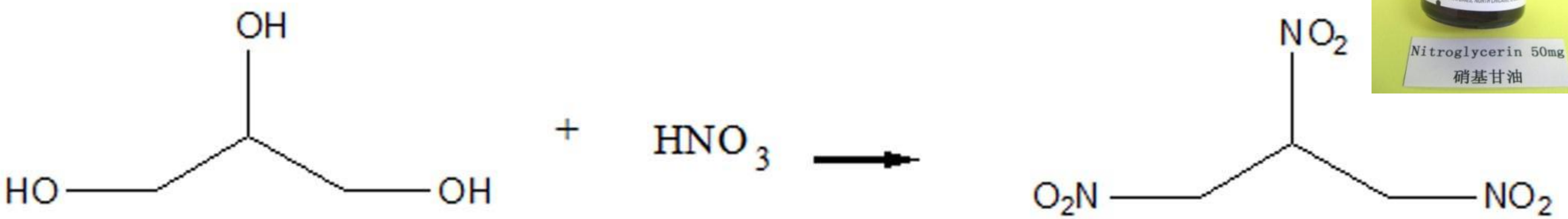
由此可見物品製造者和經營者將會選擇公佈對其產品最佳之LCA.所以做為消費者或管理(政府)要從最易發生爭議處作深入瞭解.比如說目標及範疇的界定、數據(全球對地方)之選用、數據之可靠性及未知之數據如何處理.

總結言之,LCA可增加物質、能量之效率.減少廢物.改良步驟及製程來保護環境及健康,增加安全.

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.

即時分析為防止污染: 分析需更加發展出能即時和在線上監控和管理在危險物質發生之前.

Synthesis of nitroglycerin



循環方式混合甘油及酸反應爐,不再攪拌.
利用如同一水的噴射器,將酸從噴口噴出,產生的真空將甘油吸入,不但混合非常均勻,將監控放在此處利用反應爐的溫度來甘油和酸的比例.
在反應器裝一緊急洩氣閥,在緊急狀況時(如溫度過熱)打開此閥將真空打破,甘油就會停止供應.以上諸多即時監控及分析裝使得製造硝化甘油比以往安全 .

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 for chemical accidents, including releases, explosions, and fires.

本質上更安全的化學為防止意外: 在化學反應中由一物質形成另一物質應該選擇能縮小化學意外,包括了釋出(能)、爆炸及火災之可能性.

火: 不適當化合物混合、意外點火、危險動作如燒焊、抽菸、外來的因素如撞擊、閃電、其他地方延燒過來等都能引起火災.

爆炸: 火、撞擊、高壓氣體、不能控制放熱反應等能引起爆炸.

釋出有毒物質和釋出腐蝕物質: 火燒、爆炸以及不當的化合物混合都有可能.

除了以之第三至六及十一條之外,預防化學反應引起的災難還有庫存極小化和過程簡單化.

庫存極小化: 化工業應儘量將有害物質之庫存極小化以防止災情.

和第十一條一樣要在設計時即將影響安全因素做全盤考慮.以下是要點.

反應物或生成物(包括副產品)會不會爆炸?如會,要掌握爆炸的條件,切實避免之.

如放熱反應,溫度會不會失控?會不會增至比溶劑的沸點還高?有沒有冷卻系統?

有無氣體釋出.如有,通風系統要加強.

人員要經常教育和演習以熟悉防災步驟及使用防災器材.

印度Bhopal氰化物毒氣事件.

1984年12月2日深夜氰化物毒氣由美國Union Carbide Corporation(UCC)設在印度Bhopal的生產農藥殺蟲劑化學工廠釋出,隨風飃至附近社區.居民在睡夢中不知不覺吸入毒氣,造成數千人死亡,數萬人受傷.人稱是史上最嚴重的化工災難.


實驗室安全 甘魯生, ”實驗室意外和實驗室安全” , (2011), 化學. **68**, 313-319.

”實驗室安全事件後續” , (2012), 化學. **70**, 193-194.

Condensed Principles of Green Chemistry

P - Prevent wastes
R - Renewable materials
O - Omit derivatization steps
D - Degradable chemical products
U - Use safe synthetic methods
C - Catalytic reagents
T - Temperature, Pressure ambient
I - In-Process Monitoring
V - Very few auxiliary substances
E - E-factor, maximise feed in product
L - Low toxicity of chemical products
Y - Yes, it is safe

S. L. Y. Tang, R. L. Smith, and M. Poliakoff, Principles of green chemistry: PRODUCTIVELY, Green Chem., 2005, *7*, 761-762.

Course Organization by Theme and Green Chemistry Principles

General Theme	Green Chemistry Principle
Pollution and Waste Prevention	Prevent waste
	Maximize atom economy
	Design less hazardous chemical synthesis
	Avoid chemical derivatives
	Design for degradation
	Analyze in real time for pollution
Energy (usage minimization; alternative sources)	Increase energy efficiency
	Use renewable feedstocks
	Use catalysts
Safety (workers, general population, environment)	Design safer chemicals and products
	Use safer solvents and reaction conditions
	Minimize the potential for accidents

The Twelve Principles of Green Engineering 化學工業12項原則

Anastas, P.T., and Zimmerman, J.B., "Design through the Twelve Principles of Green Engineering", Env. Sci. and Tech., 37, 5, 94A-101A, 2003.

Inherent Rather Than Circumstantial 天然優於人工

Designers need to strive to ensure that all materials and energy inputs and outputs are as inherently nonhazardous as possible.

Prevention Instead of Treatment 預防優於善後

It is better to prevent waste than to treat or clean up waste after it is formed.

Design for Separation 高瞻遠矚

Separation and purification operations should be designed to minimize energy consumption and materials use.

Maximize Efficiency 物(包括能及時間)盡其用

Products, processes, and systems should be designed to maximize mass, energy, space, and time efficiency.

Output-Pulled Versus Input-Pushed 順勢而為

Products, processes, and systems should be "output pulled" rather than "input pushed" through the use of energy and materials.

Conserve Complexity 避免節外生枝

Embedded entropy and complexity must be viewed as an investment when making design choices on recycle, reuse, or beneficial disposition.

Durability Rather Than Immortality 耐用但不能不朽

Targeted durability, not immortality, should be a design goal.

Meet Need, Minimize Excess 樸實

Design for unnecessary capacity or capability (e.g., "one size fits all") solutions should be considered a design flaw.

Minimize Material Diversity 不能『鼯鼠五技而窮』

Material diversity in multicomponent products should be minimized to promote disassembly and value retention.

Integrate Material and Energy Flows 不能華而不實

Design of products, processes, and systems must include integration and interconnectivity with available energy and materials flows.

Design for Commercial "Afterlife" 天生我材必有用

Products, processes, and systems should be designed for performance in a commercial "afterlife."

Renewable Rather Than Depleting 再生優於耗盡

Material and energy inputs should be renewable rather than depleting.

Principles of Green Engineering

I - Inherently non-hazardous and safe
M - Minimize material diversity
P - Prevention instead of treatment
R - Renewable material and energy inputs
O - Output-led design
V - Very simple
E - Efficient use of mass, energy, space & time
M - Meet the need
E - Easy to separate by design
N - Networks for exchange of local mass & energy
T - Test the life cycle of the design
S - Sustainability throughout product life cycle

S. Tang, R. Bourne, R. Smith and M. Poliakoff, The 24 Principles of Green Engineering and Green Chemistry: "IMPROVEMENTS PRODUCTIVELY", Green Chem., 2008, 10, 268–269.

Case 1.

Pregabalin (Lyrica®)

A Drug for the treatment of Neuropathic Pain

Case 2.

Sildenafil Citrate

The Active pharmaceutical ingredient (API) in the PDE_5 Inhibitor Viagra™

Case 3.

Ibuprofen

One of core non-steroidal anti-inflammatory medicines

Case 4.

Disodium iminodiacetate (DSIDA)

A key intermediate in the production of Roundup® herbicide

Fine chemicals

acrylonitrile to acrylamide → polyacrylamide

The chemical manufacturing process involves hydration of acrylonitrile at 70–120 °C by Raney copper resulting in a large volume of toxic wastes and HCN. In addition to acrylamide, *Rhodococcus rhodochrous* J1 was also used to prepare a variety of amides in high concentration and throughput in water

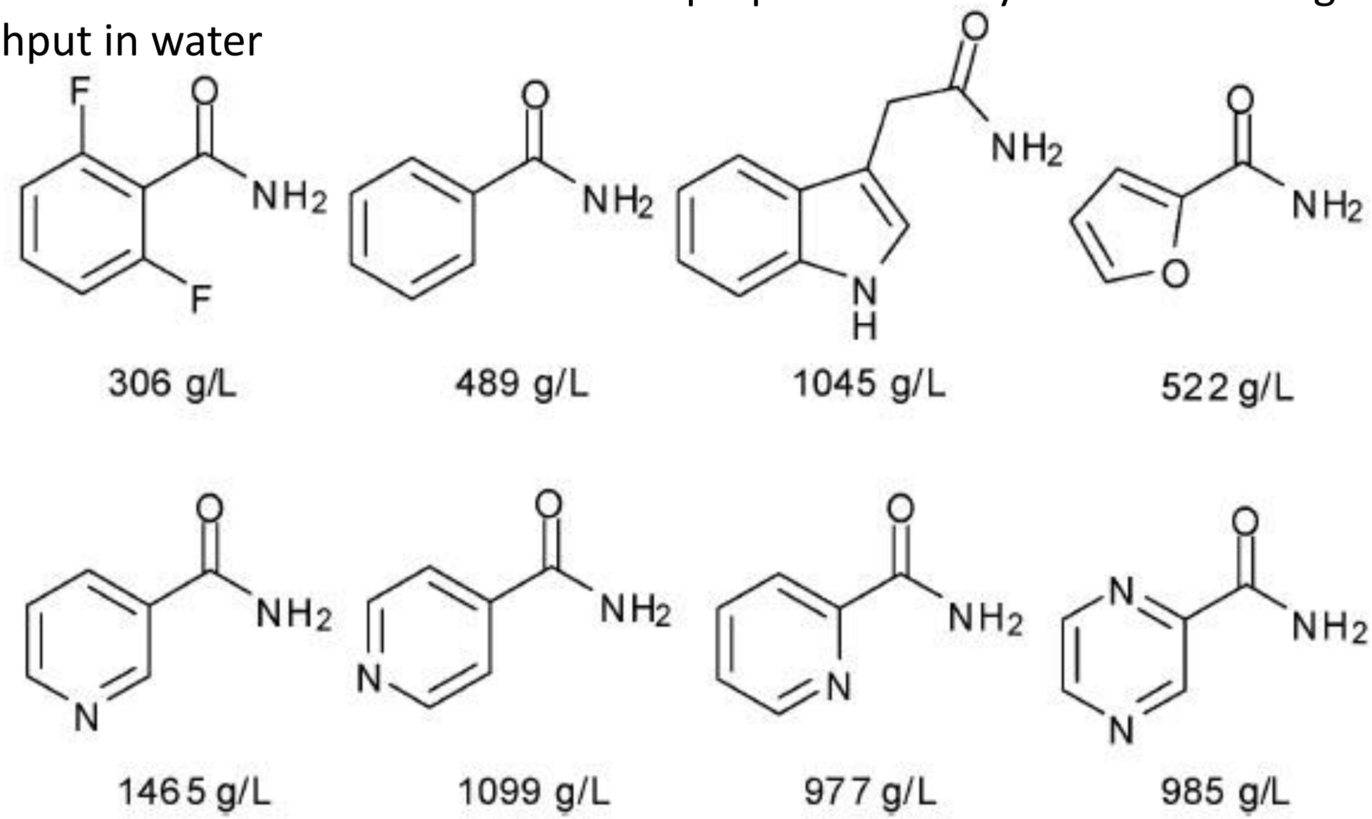
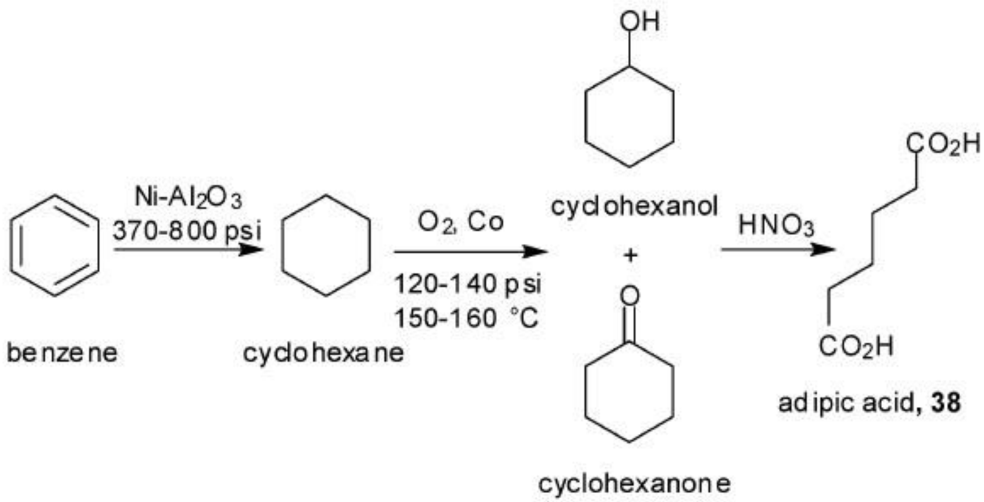


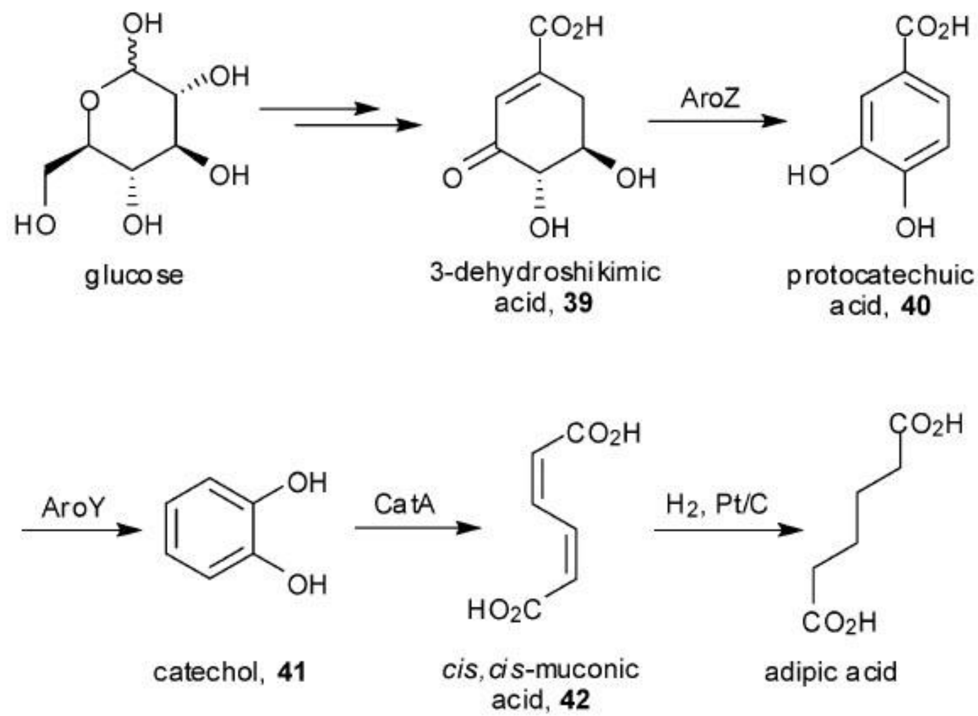
Fig. 1 Products and concentrations catalyzed by *Rhodococcus rhodochrous* J1.

Adipic acid (1,3-propanediol)(**38**), one of the monomers used in the manufacture of nylon 6,6, is currently produced at 2.2 million metric tons per year.

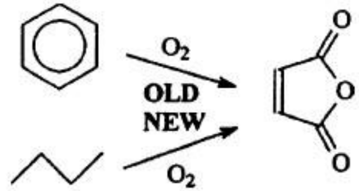
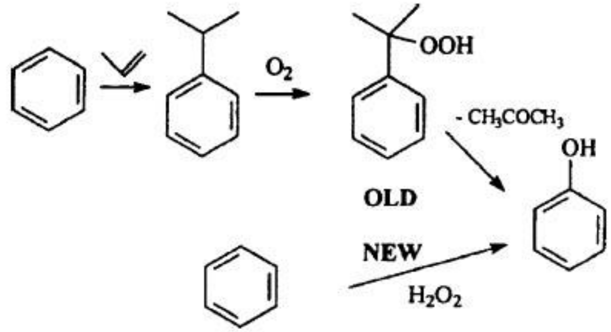
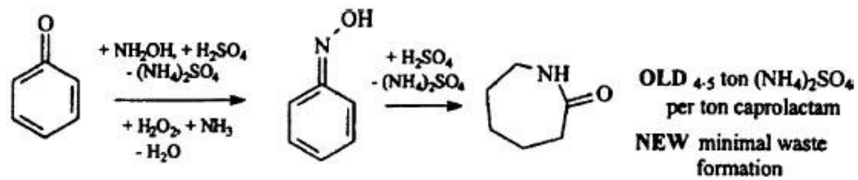
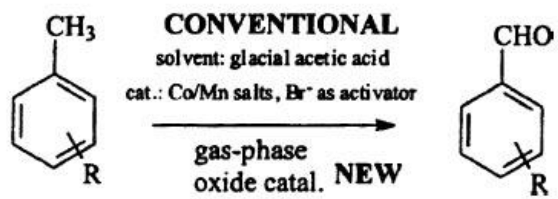
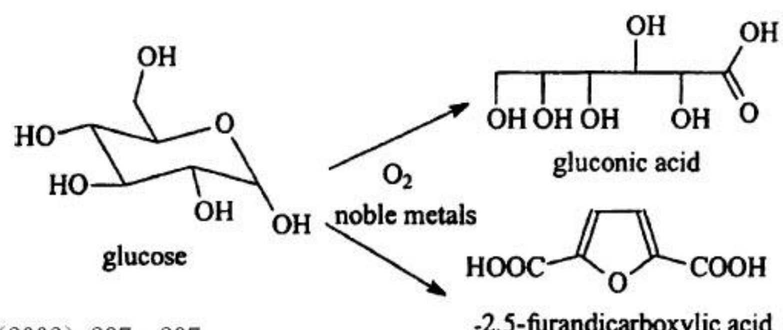


Klebsiella pneumoniae aroZ-encoded 3-dehydroshikimate dehydratase, *aroY*-encoded protocatechuate decarboxylase, and *Acinetobacter calcoaceticus catA*-encoded catechol 1,2-dioxygenase

Green Chem., 2008, ***10, 361–372***

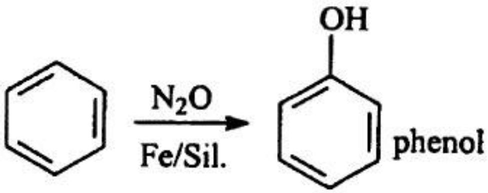
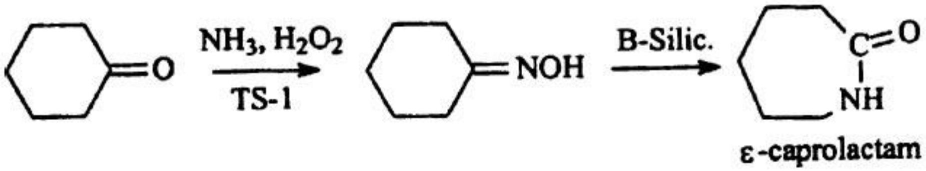
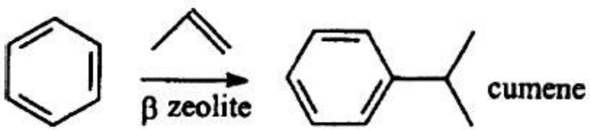
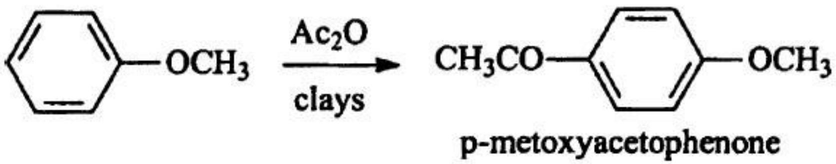
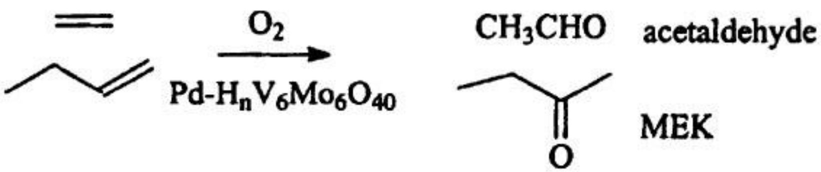
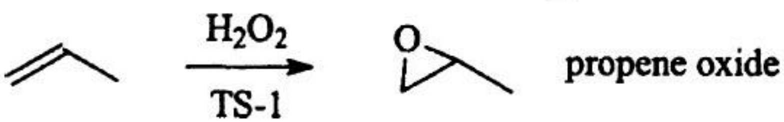
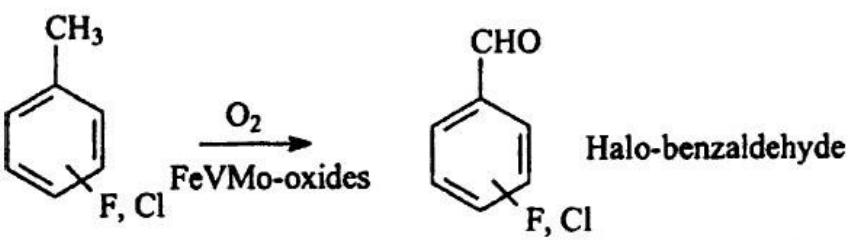


Comparison of the principles of green chemistry and objectives of industrial catalysis

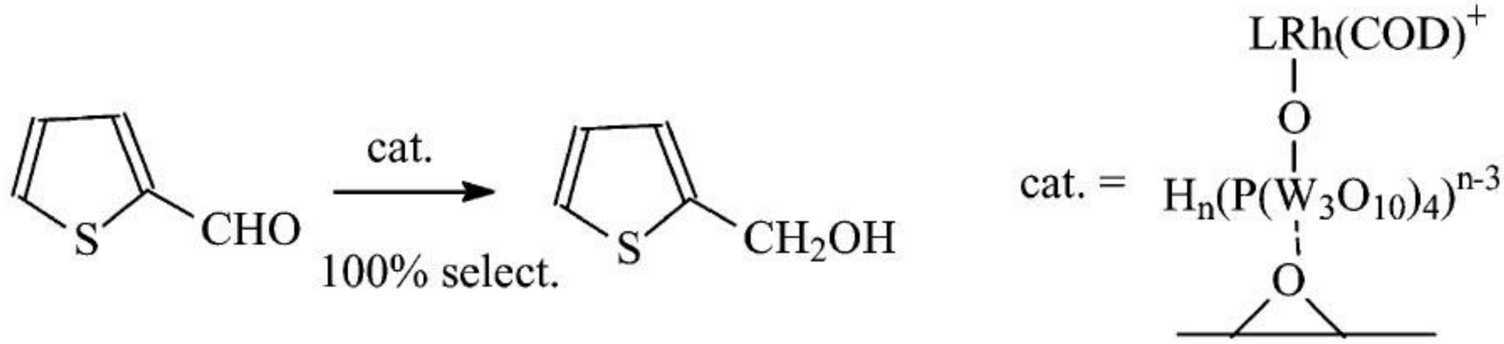
Principles of "green chemistry"	Objectives of industrial catalysis	Examples
Atom economy ("how much of the reactants end up in the product?")	Avoid side reactions (maximize selectivity), rational use of hydrocarbons	
Simple and safe process	Reduce process complexity and formation of intermediates by making in a single step over a solid catalyst complex multistep reactions	
No waste	Reduce or avoid waste formation	
Avoid toxic chemicals or solvents	Avoid solvents using heterogeneous catalysis	
Use of renewable resources	Use of natural resources for production of chemicals	

G. Centi, S. Perathoner / Catalysis Today 77 (2003) 287–297

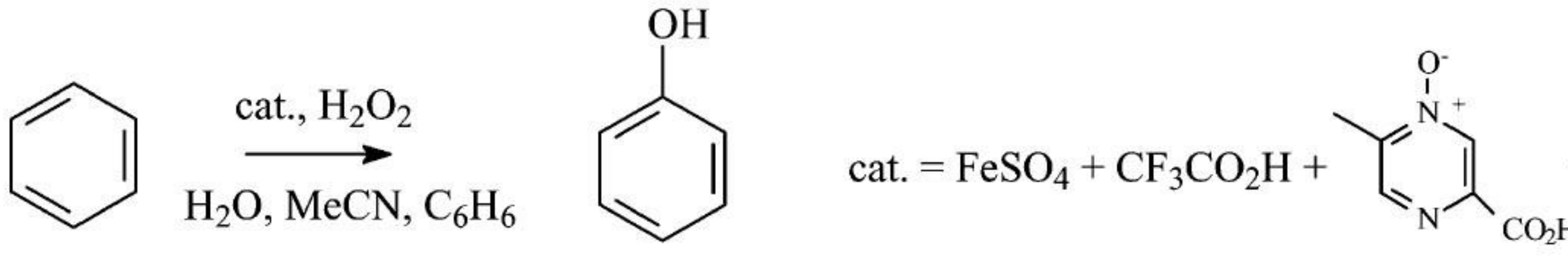
Examples of new eco-efficient catalytic processes

Process	Key characteristics
	Solutia process Reduction of N_2O emissions (greenhouse gas) by reuse as reactant
	EniChem process Reduction of ammonium sulfate waste Avoids use of toxic hydroxylamine
	EniChem process Reduction of polyalkylate waste
	Rhodia process Avoids use of hazardous catalysts such as $AlCl_3$, BF_3 Reduced waste formation
	Catalytica process Reduced formation of chlorinated waste
	EniChem process Avoids chlorinated organic by-products (with respect to the chlorohydrin process)
	Aventis process Reduced waste formation Reduced corrosion problems

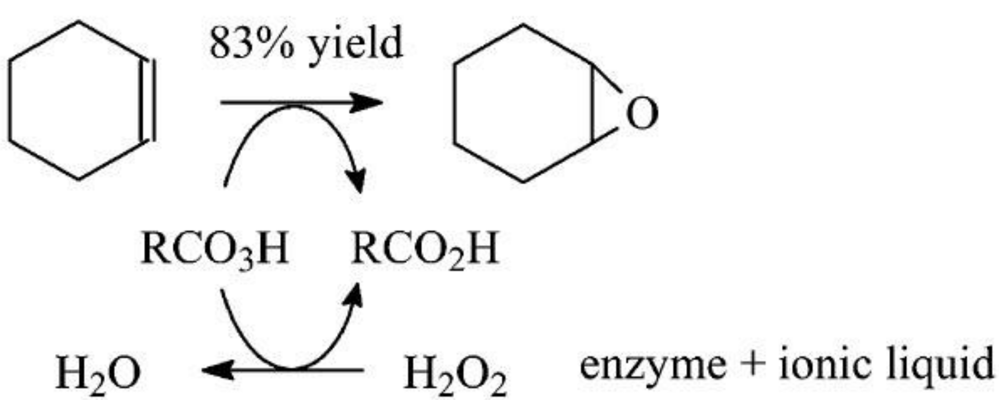
G. Centi, S. Perathoner / Catalysis Today 77 (2003) 287–297



(a)



(b)

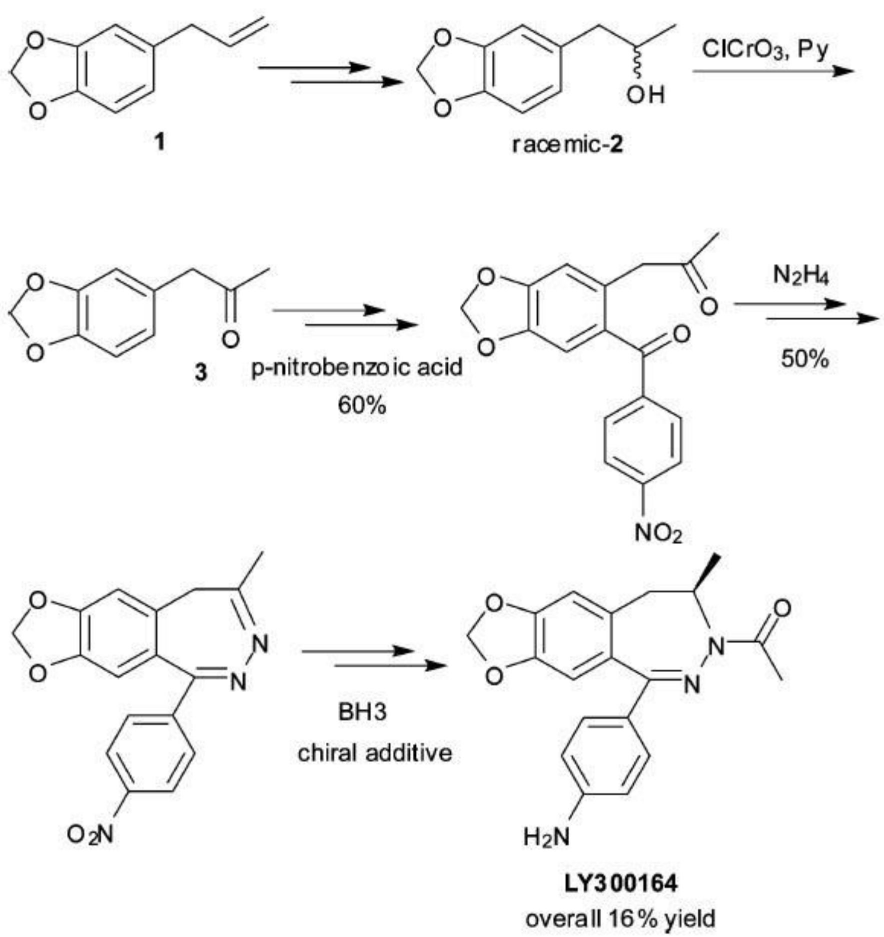


(c)

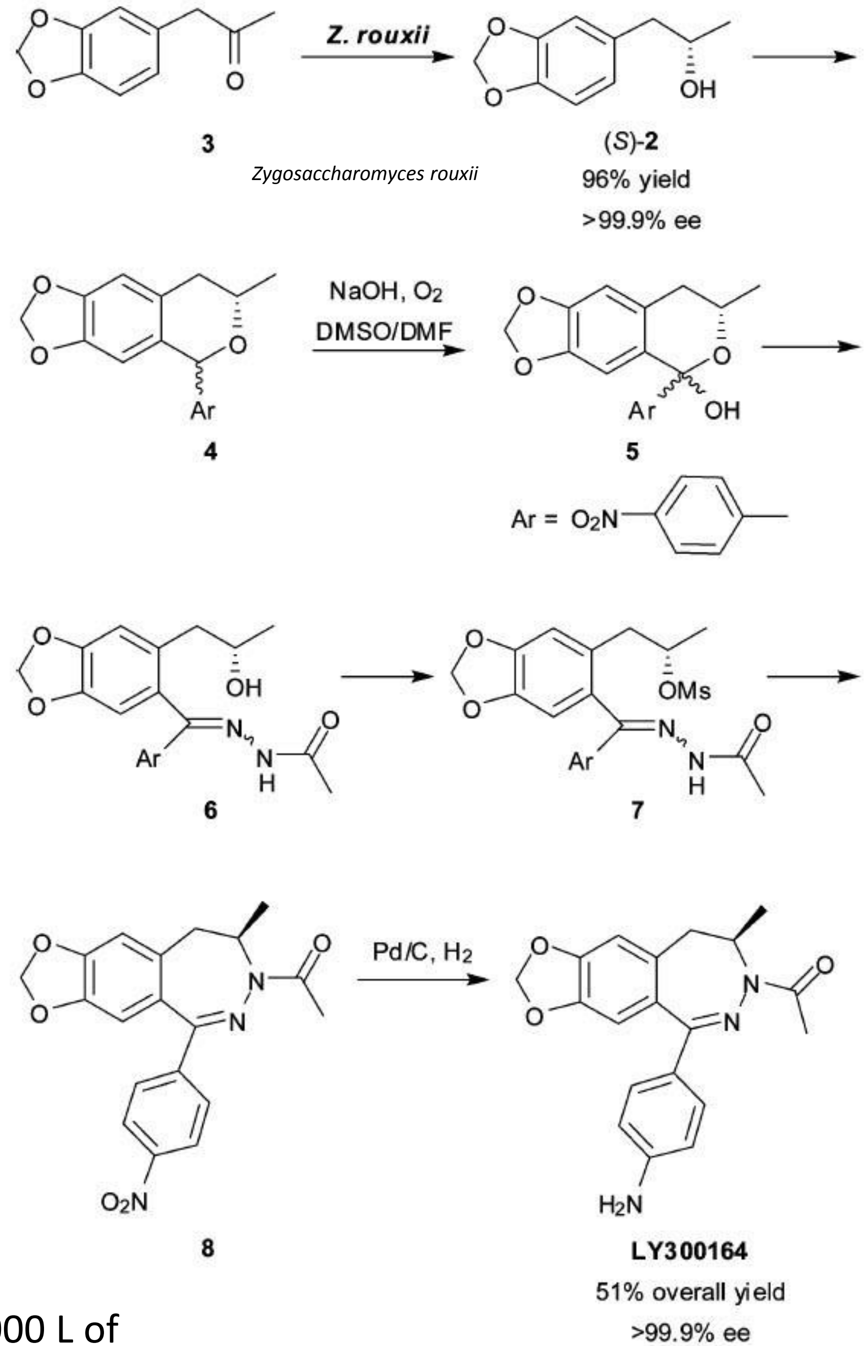
Examples of new catalytic reactions of green chemistry.

[a] R.A. Sheldon, I.W.C.E. Arends, H.E.B. Lempers, Catal. Today 41 (1998) 387.
[b] D. Bianchi, R. Vignola, Angew. Chem. Int. Ed. 39 (2000) 4321.
[c] R. Sheldon, Org. Lett. 2 (2000) 4189.

Synthesis of LY300164 (Talampanol)



Scheme 1



Scheme 2

Overall yield improved to 51% from 16% in the old route.
Every 1000 kg of LY300164 produced approximately 340 000 L of solvents and 3000 kg of chromium waste were eliminated.

Pregabalin

Using of lipase to eliminate the usage of over thousands of metric tons of raw materials including mandelic acid, CNDE and nickel, and tens millions of gallonsof alcoholic solvents and THF associated with the classic resolution route.

Atorvastatin calcium (active ingredient of Lipitor)

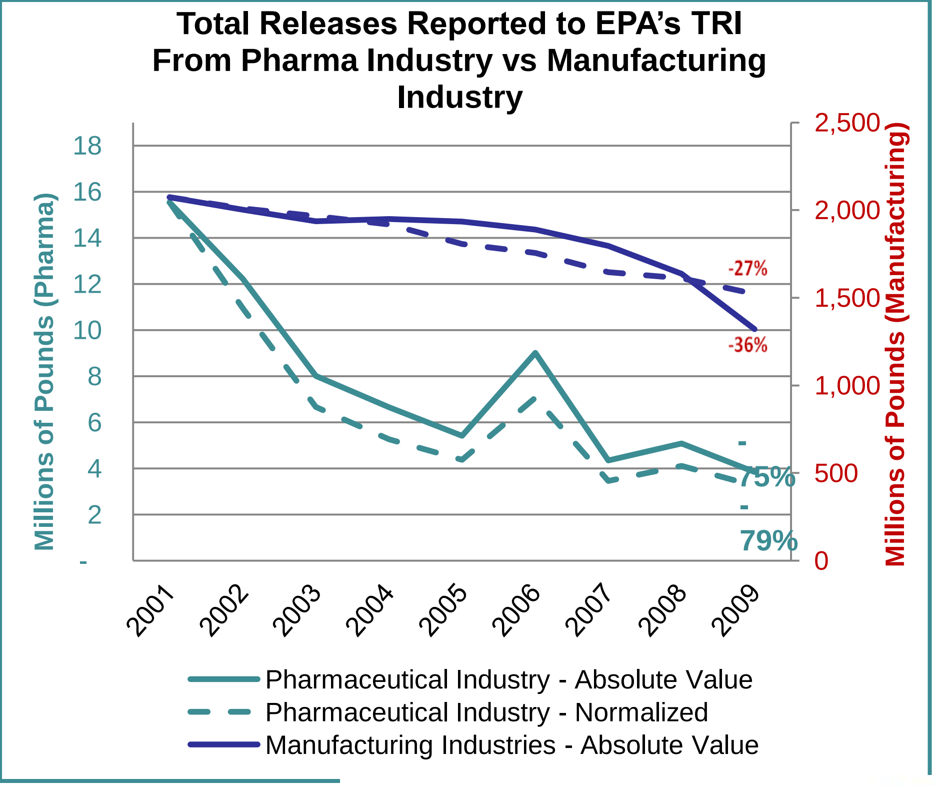
hundreds of metric tons of raw materials and solvents will be reduced each year by using the chemoenzymatic route in concomitant with significant reduction in energy consumption.

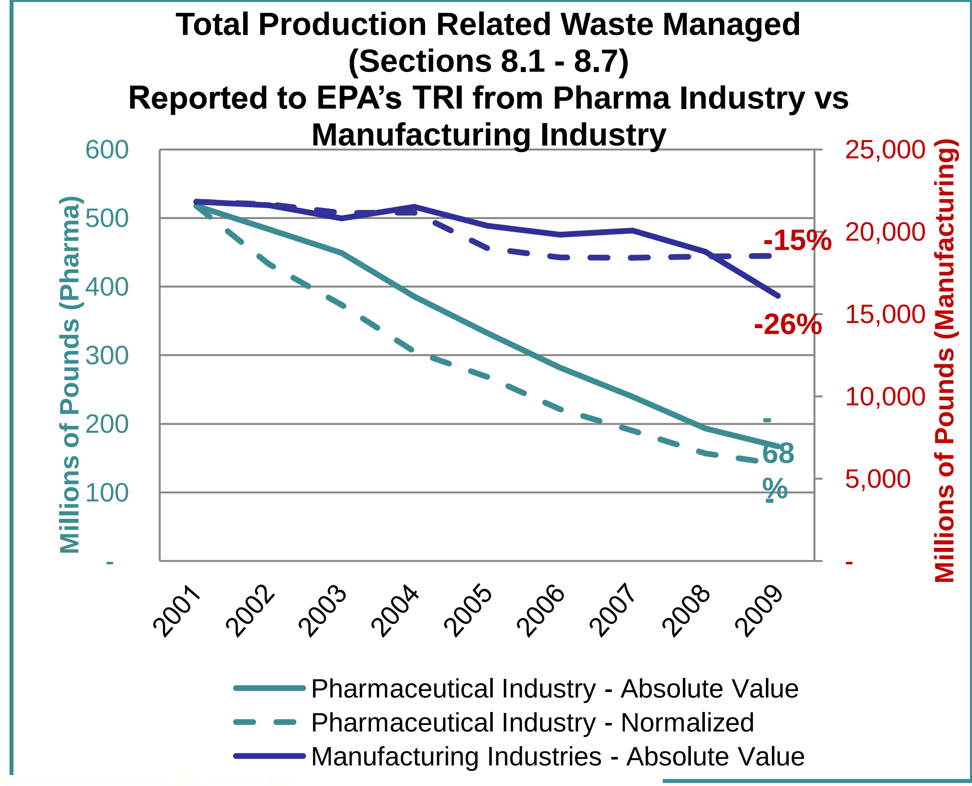
The side chain of rosuvastatin (API of Crestor)

β-lactam antibiotics such as ampicillin, amoxicillin, cefaclor, cephalexin and cefadroxil

Paclitaxel (Taxol)

Oseltamivir phosphate (Tamiflu)





334 | *16 Future Trends for Green Chemistry in the Pharmaceutical Industry*

Table 16.1 Current and aspirational E factors for industry segments.

Roger Sheldon 1992			Aspiration target	
Industry segment	E-factor		Industry segment	E-factor
Bulk chemicals	1–5	⇨	Bulk chemicals	Low
Fine chemicals	5–50		Fine chemicals	1–5
Pharmaceuticals[a]	25–>100		Pharmaceuticals[a]	5–>50

a) Refers to small molecule pharmaceutical drugs not biologics.

Biological Engineering (*Biotechnology*) Growth hormones, genetic engineering (Biocatalysts)

energy efficiency (at ambient temperature under ambient atmosphere) and safe

high stereo and regio-selectivity,

preventing or limiting the use of hazardous organic reagents

Avoiding extensive protection and deprotection sequences

In water

Studies showed that among the 1039 chemical transformations analyzed for the synthesis of 128 drug molecules (to 2008).

J. S. Carey, D. Laffan, C. Thomson and M. T. Williams, Analysis of the reactions used for the preparation of drug candidate molecules, *Org. Biomol. Chem.*, 2006, **4**, 2337–2347.

D. J. C. Constable, P. J. Dunn, J. D. Hayler, G. R. Humphrey, J. L. Leazer, Jr., R. J. Linderman, K. Lorenz, J. Manley, B. A. Pearlman, A. Wells, A. Zaks and T. Y. Zhang, Key green chemistry research areas—a perspective from pharmaceutical manufacturers, *Green Chem.*, 2007, **9**, 411–420.

Stage 1: Field leveling, terracing *Civil Engineering* irrigation ditches
Stage 2: Plows, tractors *Mechanical Engineering* a tool for every task
Stage 3: Fertilizers *Chemical Engineering* herbicides, pesticides
Stage 4: Growth hormones *Biotechnology* genetic engineering (*Biological Engineering)*
所以生物科技是解決問題的希望.比如說基因改良可使農作物抗旱、抗害蟲等也許可免除化學物的施放.但是我們對未來永遠充滿了疑惑.

永續(綠色)化學與永續(綠色)工程：
永續化學之精義是設計化學產物及過程時要減少或消除廢物及有毒物質之產生。永續工程的意義是生產商品時要降低對人類健康及環境的危害，在過程中也要符合經濟原則，都是生產必需用品但不污染環境。所以永續化學和永續工程是延續人類生存的重大基石。本課程闡述永續化學和永續工程十二項原則並佐以實例，俾使人人有正確的認識並落實於生活之中。

Green Chemistry Is About...

Reducing

- Waste
- Materials
- Hazard
- Risk
- Energy
- Cost

誌謝: 綠色/永續合成化學工作坊 趙奕姼 劉廣定 周德璋 廖俊臣 吳丁凱
沙晉康 許拱北 陳月枝 蔡蘊明
中央研究院化學研究所 郭燕玲 賴俐位
中國化學會 化學與環境委員會
行政院國家科學委員會 化學推廣中心

謝謝大家