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# Chemistry Innovations in Sustainable Development

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## 'Learning-by-Notes' Package for Senior School

### Lesson 11: Green Chemistry *Reducing Toxicity*

#### Teaching Sustainability in High Schools: Subject Supplement

Developed by:



The Natural Edge  
PROJECT



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### **The Natural Edge Project**

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# Lesson 11: Green Chemistry

## Reducing Toxicity

*The products of the chemical industry are worth US \$1,500 billion annually, and account for approximately 9 per cent of world trade in manufactured goods.*

**The Organisation for Economic Co-operation and Development  
Environment, Health and Safety Programme<sup>1</sup>**

*As designers of molecules, materials, products, processes and systems, chemists play an important role in developing the future healthy chemicals economy.*

**Clean Production Action<sup>2</sup>**

### Educational Aim

This lesson aims to introduce the topic of reducing toxicity and the concept of 'benign by design', where products and services are designed so that they don't use or produce toxins in the first place. The lesson provides examples of companies and organisations that are successfully applying this concept to their products and services.

### Key Words for Searching Online

Green Chemistry Resources, Green Chemistry Institute, US EPA Green Chemistry Program, Green Chemistry Journal, Green Chemistry Network, US EPA Presidential Green Chemistry Challenge, Green solvents, zero toxicity, ClimaTex fabric,

### Key Learning Points

1. While the chemical industry has contributed significantly to human development over the last century (see Lesson 9), Rachel Carson's 1962 publication *Silent Spring*<sup>3</sup> demonstrated that at times this has occurred at the expense of human health and the environment. Rachel showed that some chemicals like Mercury and Hexachlorobenzene (HCB) can 'bio-accumulate' (stored in fatty tissue as predators eat their prey) up the food chain, posing a risk to both human and environmental health. Chemicals called endocrine or hormone disruptors can also harm the reproductive systems of humans and wildlife.
2. As awareness of these issues has improved over the last half century, green chemistry is being increasingly seen as a viable alternative to producing toxic products and toxic waste. The application of green chemistry can reduce risks to health and safety, help the

<sup>1</sup> OECD (2005) *The OECD Environment, Health and Safety Programme*, OECD, Paris.

<sup>2</sup> Greiner, T., Rossi, M., Thorpe, B. and Kerr, B. (2006) *Healthy Business Strategies for Transforming The Toxic Chemical Economy, Clean Production Action*. Available at <http://www.cleanproduction.org/library/CPA-HealthyBusiness-1.pdf>. Accessed February 2007.

<sup>3</sup> Carson, R. (1962) *Silent Spring*, Houghton Mifflin, Boston.

environment, reduce costs and improve a company's reputation while also opening up options to create new greener products.<sup>4</sup>

3. If we consider the design and commercialisation process for a product as a pipe, we can think of conventional 'environmental management' as attempting to clean up the pollution at the 'end of pipe', once all of the design and production processes have been completed. The challenge of green chemistry is to reduce toxicity in the product and in the waste stream, by *designing out* the toxicity in the first place - i.e. moving back up the pipe to the beginning and designing products that are 'benign by design'.
4. Applying the green chemistry and green chemical engineering principles presented in Lesson 9 helps to create products that are 'benign by design' in the following ways:<sup>5</sup>
  - Identifying the most ecologically sustainable and benign chemical reaction processes, solvents and chemicals to create the desired outcome, involving no toxic chemicals and no toxic waste.
  - Designing reactions so that as many of the atoms as possible that are present in the starting materials end up in the product rather than in the waste stream – i.e. being atom efficient, and thus preventing waste production.
  - Incorporating chemical synthetic approaches that are less toxic as well as being atom efficient.
  - Creating chemical reactions that either produce no waste, biodegradable waste, or waste that can be used as a resource in other industrial chemical processes.
5. Green chemistry and green engineering are now being practised and promoted by a number of the major companies internationally. For example, 3M began its 'Pollution Prevention Pays' program in 1977, which the company estimates saved them US\$750 million and reduced their waste by 1.2 billion pounds (approximately 0.5 billion kilograms) by the late 1990s. Companies such as 3M, Dupont, Dow, Herman Miller and Interface Ltd are now adopting green chemistry<sup>6</sup> and green engineering<sup>7</sup> approaches.
6. US based international carpet company, *Interface Ltd*, is replacing petrochemical based carpets with carpets made from renewable biomass, such as corn waste, that can be recycled with little loss of quality. Interface has now reduced its environmental footprint by more than 40 per cent, cut total carbon dioxide emissions by 56 per cent, decreased total energy consumption required to manufacture carpet by 43 per cent, eliminated over US\$300 million in waste since 1995.<sup>8</sup> The company claims that chemicals used in the carpet are so non-toxic that they can safely be eaten! Examples of the company's innovations include:
  - Residential carpet products are manufactured from a renewable, corn-based polymer called 'polylactic acid' (PLA).

<sup>4</sup> La Merrill, M., Parent, K. and Kirchoff, M. (2003) 'Green Chemistry-Stopping Pollution Before it Starts', *ChemMatters*, April, pp7-10.

<sup>5</sup> Ritter, S.K. (2001) 'Green Chemistry', *Chemical & Engineering News*, Vol. 79, pp27-34; Ryan, M. (1999) 'Benign by Design', *ChemMatters* December 1999, pp9-11; Collins, T. (2001) 'Toward Sustainable Chemistry', *Science*, Vol. 291, pp48-49; Anastas, P. T. and Warner, J. C. (1998) *Green Chemistry: Theory and Practice*, Oxford University Press, New York; McDonough, W. and Braungart, M. (1998) 'The Next Industrial Revolution', *The Atlantic Monthly*, October 1998, pp82-92; Graedel, T. (1999) 'Green Chemistry in an industrial ecology context', *Green Chemistry*, Vol. 1, pp126-128.

<sup>6</sup> Clark, J. (1999) 'Green chemistry: Challenges and Opportunities', *Green Chemistry*, Vol. 1, pp1-9.

<sup>7</sup> Ritter, S.K. (2002) 'Green Chemistry Gets Greener', *Chemical & Engineering News*, Vol. 80, pp38-42.

<sup>8</sup> Garrett, K. (2001) 'Natural Capitalism – A Lecture by Amory Lovins', *Radio National*, Australian Broadcasting Company (ABC). Available at [www.abc.net.au/rn/talks/bbing/stories/s231834.htm](http://www.abc.net.au/rn/talks/bbing/stories/s231834.htm). Accessed 5 January 2007.

- Commercial panel and upholstery fabrics are manufactured from fibres containing 100 per cent post-consumer recycled polyester or 100 per cent renewable PLA.
  - The company now offers the first certified 'climate-neutral' carpet product in the world, where emissions associated with the carpet's manufacture have been reduced, then offset.
7. US based international furniture company *Steelcase* has also used green chemistry to replace a textile for chair backings whose end trimmings had been declared a 'toxic waste' by the Swiss Government, because of heavy metals used in treating and dyeing the cloth. The company identified about 8,000 chemicals used in the cloth business, and they eliminated from consideration any chemicals that caused cancer, mutations, birth defects, endocrine disruption, bio-accumulation or persistent toxicity. This left them with 38 safe chemicals from which the company realised it could still make every colour. Additional benefits included the fact that the cloth looked and felt better, lasted longer (because the natural fibres they used were no longer being degraded by harsh chemicals), and cost less to produce. When the Swiss environmental inspectors came to inspect the factory discharge after the process had been changed, they thought their measuring equipment must be broken because the water coming out was actually cleaner than the Swiss drinking water going in!<sup>9</sup>
  8. Leading research institutions around the world now have green chemistry research programs, which is helping to advance knowledge rapidly and create new ways for industry to reduce toxic chemical use. Large chemical industry bodies in the UK, Australia and Europe are also embracing sustainable chemistry, launching major programs in recent years.
  9. In some places around the world business, government and universities are working together to dramatically reduce the amount of toxic chemicals used in industry. For example in 1989, a partnership between a group of responsible industries, citizen groups and the University of Massachusetts resulted in the Commonwealth of Massachusetts' Toxic Use Reduction Act.<sup>10</sup> The stretch goal was a 50 per cent reduction in toxics by 1997 without any lost profits or business competitiveness.<sup>11</sup> Dr Samuel Epstein, a tough critic of the chemical industry was even impressed, stating that, "*These industries said, 'Look, if you can show us how to go on about our business without losing money, then we'll work with you'. The results of the law have been phenomenal. Over the past decade, for example, hazardous organic solvents have been substantially phased out and replaced by safer alternatives*".<sup>12</sup>
  10. Shifting away from using fossil fuels to other less-polluting alternatives is a significant potential contribution to reducing GHG emissions, but will also be an important way to address the globally diminishing supply of oil - considering that approximately 98 per cent of all organic chemicals synthesised currently come from petroleum feedstocks!<sup>13</sup> The reagents used by the chemical industry, today mostly derived from oil (i.e. fossilised carbon), are likely to increasingly be obtained from renewable sources. Other examples of renewable feedstock use, include:

<sup>9</sup> McDonough, W. and Braungart, M. (2002) *Cradle to Cradle: Remaking the Way We Make Things*, North Point Press, NY.

<sup>10</sup> US EPA (1994) *The Massachusetts Toxics Use Reduction Institute – Fact Sheet 1*, Envirosense Repository. Available at <http://es.epa.gov/techinfo/facts/mass/tura-fs1.html>. Accessed 12 December 2007.

<sup>11</sup> See Toxics Use Reduction Planners Association (TURPA) - *About the Toxics Use Reduction Act* at [www.turpa.org/about/the\\_tura\\_program/about\\_the\\_toxics\\_use\\_reduction\\_act.html](http://www.turpa.org/about/the_tura_program/about_the_toxics_use_reduction_act.html). Accessed 12 December 2007.

<sup>12</sup> Epstein, S. (2000) 'An Epidemic of Cancer Deception: The Establishment, Why We Can't Trust Them - An Interview With Samuel Epstein', *The Sun Magazine*, March 2000, Issue 291. A copy of this article is available at <http://www.health-communications.com/prepedemic3-02-02.html>. Accessed 12 December 2007.

<sup>13</sup> Collins, T. (2001) 'Toward Sustainable Chemistry', *Science*, Vol. 291, pp48-49. Available at <http://www.chemistry.org/portal/a/c/s/1/acdisplay.html?DOC=education%5cgreenchem%5cgreenreader.html>. Accessed 12 December 2007.

- Metabolix Inc: a bio-industrial company working to create large scale technologies for the development of water resistant, biodegradable bioplastics (PHAs) through fermentation of natural oils and sugars using microbial factories.<sup>14</sup>
  - Interface Inc: a carpet company who have developed a range of carpet fabrics and backings from corn-based polymers, and who are now 100 per cent recyclable/compostable.<sup>15</sup>
11. Thus, adopting a 'benign by design' approach to the design and manufacture of products can provide opportunities to reduce or eliminate waste and toxicity during the upfront design process, reducing the subsequent costs of pollution control and waste disposal costs.

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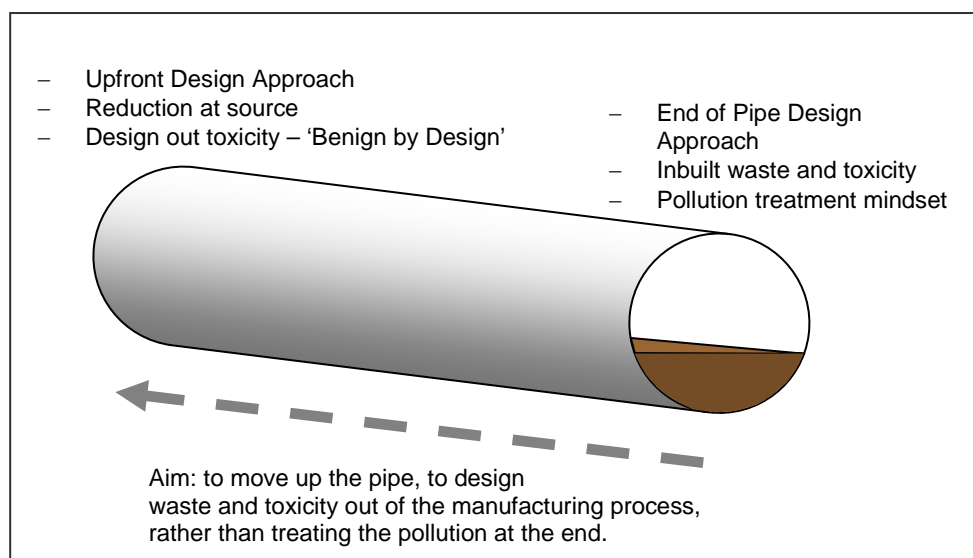
<sup>14</sup> Metabolix (2002) 'Metabolix Produces Sustainable, Affordable Alternative to Petrochemical Plastics', Press Release, Metabolix Inc. Available at <http://www.metabolix.com/publications/pressreleases/PRmay2002.html>. Accessed 12 December 2007.

<sup>15</sup> See Interface Inc - *Interface, Inc. – What we Do* at <http://www.interfaceinc.com/what/>. Accessed 12 December 2007.

## Brief Background Information

### *Benign by Design: Source Reduction Rather than End of Pipe*

If we consider the design and commercialisation process for a product as a pipe (see Figure 11.1), we can think of conventional 'environmental management' as attempting to clean up the pollution at the 'end of pipe', once all of the design and production processes have been completed. The challenge of green chemistry is to reduce toxicity in the product and in the waste stream, by *designing out* the toxicity in the first place - i.e. moving back up the pipe to the beginning and designing products that are 'benign by design'.



**Figure 11.1:** A Diagrammatic representation of moving the design 'up the pipeline', to design waste out of the product, making it 'benign by design'

Source: The Natural Edge Project (2008)

Designing out toxic waste 'upfront' is achieved using the principles of green chemistry and green chemical engineering (presented in Lesson 9), which can be applied in the following ways:<sup>16</sup>

- Identify the most ecologically sustainable and benign chemical reaction processes, solvents and chemicals to create the desired outcome.<sup>17</sup>
- Design chemical reactions so that as many of the atoms as possible that are present in the starting materials end up in the product rather than in the waste stream – i.e. being atom efficient, and thus preventing waste production.<sup>18</sup>
- Use chemical synthetic approaches, which have been created in both industry and academia to produce far less waste (are atom efficient) while being significantly more environmentally benign.<sup>19</sup>

<sup>16</sup> Ritter, S.K. (2001) 'Green Chemistry', *Chemical & Engineering News*, Vol. 79, pp27-34.

<sup>17</sup> Collins, T. (2001) 'Toward Sustainable Chemistry', *Science*, Vol. 291, pp48-49.

<sup>18</sup> Anastas, P. T. and Warner, J. C. (1998) *Green Chemistry: Theory and Practice*, Oxford University Press, New York.

<sup>19</sup> For a good example see US EPA Presidential Green Chemistry Challenge (1996) *The catalytic dehydrogenation of diethanolamine*, US EPA. Available at <http://www.epa.gov/gcc/pubs/pgcc/winners/gspa96.html> Accessed 12 December 2007.

- Design the chemical reaction or chemical industrial process so that it either produces no waste, or the waste it does produce is either biodegradable or can be used as a resource in other industrial chemical processes.<sup>20</sup>

### ***Reducing Risk by Addressing the Hazard, Not Just Exposure***

*Yet another reason for the chemistry community to pursue green chemistry (and green engineering) vigorously is because it is based on fundamental molecular science providing the root of the solutions, rather than on applying a bandage or patchwork approach to risk reduction.*

**Paul Anastas, Founder of Green Chemistry<sup>21</sup>**

At its most basic level, risk can be described by the formula '*Risk = f [hazard, exposure]*' (i.e. risk is a function of - or related to - hazard and exposure). The conventional way that society has dealt with reducing risk is by fixing the hazard at some specific level, and managing exposure. Using well-characterised hazards (for example using toxicity data) and calculating the social, health and environmental tolerance for exposure, the risk can be reduced until it is below an 'acceptable level', through national environmental legislation, regulations and policy regarding exposure control.

However, while a 1:1,000,000 cancer risk from exposure to a certain level of a substance may be defined by society in its laws and regulations as 'acceptable', this risk is calculated on current understanding of the hazard and its health implications. In addition, such estimations may not take into consideration all environmental implications of the hazard, as highlighted by Rachel Carson in her seminal book, *Silent Spring*.<sup>22</sup> Another limitation of exposure controls to reduce risk is that the use and release of a chemical may affect individuals who aren't using those controls. For instance, a chemical worker may be wearing gloves, goggles, etc. in order to protect themselves from being exposed to high levels of a certain substance known to have acute effects. But how do these exposure controls affect someone downstream or downwind who is not protected by exposure controls?

### **Considering the Hazard**

The reality is that human beings now carry as many as 200 industrial chemicals in our bodies that were invented in the past 75 years. New technological advances have helped scientists to better detect chemicals in human blood, breast milk and urine.<sup>23</sup> Simply having such chemicals in our systems does not mean that these chemicals are a health problem but also it cannot be assumed that they are having no effect.

Rachel Carson's publication *Silent Spring* was significant in raising concerns about the ability of certain chemicals to bio-accumulate through nature's food chains (i.e. as predators eat their prey

<sup>20</sup> McDonough, W. and Braungart, M. (1998) 'The Next Industrial Revolution', *The Atlantic Monthly*, October 1998, pp82-92; Graedel, T. (1999) 'Green Chemistry in an industrial ecology context', *Green Chemistry*, Vol. 1, pp126 - 128.

<sup>21</sup> Anastas, P.T. and Warner, J.C. (2000) *Green Chemistry: Theory and Practice*, Oxford University Press, Oxford.

<sup>22</sup> Carson, R. (1962) *Silent Spring*, Houghton Mifflin, Boston.

<sup>23</sup> Environmental Working Group (EWG) (2003) *Body burden: the pollution in people*, EWG; Environmental Working Group (EWG) (2005) *Body burden: the pollution in newborns*, EWG; Environmental Working Group (EWG) (2006) *Across generations: mothers and daughters*, EWG; Department of Health and Human Services, Center for Disease Control and Prevention (2005) *Third national report on human exposure to environmental chemicals*, EWG.



and store the chemicals in their fatty tissue). Persistent chemicals (or their breakdown products) can stay in our bodies for long periods of time. Bio-accumulative chemicals build up in animal and human tissue, and persistent bio-accumulative pollutants pose the greatest chemical threat to sustainability. Many characterised examples originate from the chlorine industry and are also potentially bio-accumulative. For example, polychlorinated dibenzo-dioxins and -furans are deadly, persistent organic pollutants. They can form in the bleaching of wood pulp with chlorine-based oxidants, the incineration of chlorine-containing compounds and organic matter, and the recycling of metals. The United Nations Environmental Program (UNEP) International Agreement on persistent organic pollutants lists 12 'priority' pollutant compounds and classes of compounds for global phase-out. All are organochlorines. Consider also 'endocrine-disrupting chemicals' (EDCs), such as polychlorobiphenyls (PCBs), which disrupt the body's natural control over the reproductive system by mimicking or blocking the regulatory functions of the steroid hormones or altering the amounts of hormones in the body. Our present knowledge strongly suggests that anthropogenic EDCs should be identified and removed from manufacturing processes altogether.

Many of these problems may have been avoided if society, governments and companies had acted upon early health warnings about chemicals. Concerns about the potential environmental and health impacts of chemicals are not new. Already by 1900 the risks of acid rain<sup>24</sup> (first warning 1872), asbestos<sup>25</sup> (first warning 1898), PCB's<sup>26</sup> (first warning 1899), and benzene<sup>27</sup> (first warning 1897), were known.

### Addressing the Hazard

Green chemistry has gone from academic theory to a multimillion-dollar business in the past 15 years, with companies increasingly focused on the hazards of chemicals used in their products. Historically, people have thought of economics and the environment as a trade-off — you can do well by one or the other, but not both. Green chemistry and green engineering offers a way through design to have both – to find new, cheaper, safer and more efficient ways to produce a wide range of products and services.

As Greiner *et al* stated in the *Healthy Business Strategies for Transforming the Toxic Chemical Economy*,<sup>28</sup>

*Although businesses' individual actions to address toxic chemicals vary, their best practices, when gathered together, define the terrain of healthy chemical strategies:*

- *Identify all chemicals in their products.*
- *Eliminate toxic chemicals.*
- *Strive to manufacture and use only healthy ingredients in their products.*
- *Design new products.*
- *Innovate — design new products and develop novel partnerships.*

<sup>24</sup> Smith R.A. (1872) *Air and Rain*, Longmans Green & Co., London.

<sup>25</sup> Deane, L. (1898) 'Report on the Health of Workers in Asbestos and Other Dusty Trades', in HM Chief Inspector of Factories and Workshops (1898) *Annual Report for 1898*, HMSO, London, pp171–172, (see also the Annual Reports for 1899 and 1900, p502).

<sup>26</sup> Harremo, P., Gee, P., MacGarvin, M., Stirling, A., Keys, J., Wynne, B. and Vaz, S.G. (2002) 'Late Lessons from Early Warnings: the Precautionary Principle 1896-2000', *Environmental Issue Report No 22*, European Environment Agency.

<sup>27</sup> LeNoir, C. (1897) 'On a Case of Purpura Attributed to Benzene Intoxication', *Bul. Mem. Soc. Med. Hop.*, Vol. 3, pp1251–1261.

<sup>28</sup> Greiner, T., Rossi, M., Thorpe, B. and Kerr, B. (2006) *Healthy Business Strategies for Transforming the Toxic Chemical Economy*, Clean Production Action Report. Available at <http://www.cleanproduction.org/library/CPA-HealthyBusiness-1.pdf>. Accessed 12 December 2007.

- *Work collaboratively with environmental advocates.*
- *Take responsibility for products from cradle-to-grave. Require data from suppliers on chemicals and materials used in products. Work with suppliers to create healthy ingredients. Design products to be reused, recycled or composted. Take products back at end-of-life.*
- *Adopt internal chemical policies, including the use of lower threshold of scientific certainty when threats of serious or irreversible damage to the environment become apparent - also known as the precautionary principle.*
- *Support laws that promote green chemistry and eliminate toxic chemicals.*

*Their motivations for taking action beyond compliance initiatives range from: pure business rationale such as product differentiation, cost savings and reputation management to deeply held values such as customer, community and worker health and wellbeing.*

Regulatory changes are also acting as drivers for change. The 1990 US Pollution Prevention Act was the first regulation to establish source reduction as the highest priority rather than the usual end-of-pipe approaches to solving environmental problems. Shortly after the passage of this Act it was recognised that chemists and chemical engineers were going to be needed to address the source reduction of pollution. In 1991, the Office of Pollution Prevention and Toxics in the US EPA launched the first research initiative of the Green Chemistry Program, the Alternative Synthetic Pathways research solicitation.

In Europe significant regulatory changes are also occurring, and consequently more and more companies are looking to the fields of green chemistry and green engineering. One of the most important developments is the *Registration, Evaluation, and Authorisation of Chemicals (REACH)* legislation<sup>29</sup> passed by the European Union. This initiative attempts to remedy current practice that sees tens of thousands of chemicals being used without sufficient knowledge about their environmental and health effects. Not only does REACH explicitly restrict the use of carcinogens and mutagens, but it has an additional key element that is leading to significant change - it forces consideration of alternatives as part of the chemical licensing process. REACH will therefore catalyse cleaner and greener chemical technologies and safer products globally. In preparation for its enactment in 2006, many companies in Europe and North America started phase-outs of chemicals of high concern. Individual members of the European Union went further, adopting legislation that banned the commercial production and use of carcinogens. One of the leading examples of this occurred in Sweden in 2001, where a sustainable chemical policy was passed requiring that all new chemicals proposed for use must be accompanied by evidence that they are not a carcinogenic risk.

### ***Industry Take Up – Source Reduction***

With increased regulation of the chemical industry, a high priority is now placed on developing solutions to avoid chemical treatment and remediation costs through waste prevention. Many chemical and related industries realise that re-designing waste out of the initial process will not only save significant costs but can also result in greater profits. The chemical industry has turned

<sup>29</sup> OECD (2008) OECD Environmental Outlook to 2030. OECD. Available At [http://www.oecd.org/document/20/0,3343,en\\_2649\\_37465\\_39676628\\_1\\_1\\_1\\_37465,00.html](http://www.oecd.org/document/20/0,3343,en_2649_37465_39676628_1_1_1_37465,00.html) Accessed 22.03.2008

to research institutions for guidance to reduce or eliminate the use or generation of hazardous substances in the design, manufacture and application of chemical products.<sup>30</sup>

In Australia and globally the chemicals industry has made strong commitments to achieving sustainable development. This will further help enhance the rapid take up of green chemistry approaches globally throughout the chemicals industry. More than a decade ago in their 1996 report 'Sustainable Development and the Chemical Industry' the International Council of Chemical Associations' stated, *'The global chemical industry believes that the key to improving the performance of the industry is both its commitment to achieving environmentally sound sustainable development and improved performance and transparency.'*<sup>31</sup>

In 2003, the UK Chemical Industries Association (CIA) governing Council adopted a new vision for the sector, based on an economically sustainable industry, stating that, *'By putting sustainable development at the heart of everything the industry does... CIA members are committed to the development of a safer, greener, ethically sound and prosperous UK chemical industry... the chemical industry is committed to work with all stakeholders to ensure our contribution to sustainable development will help meet society's needs and expectations.'*<sup>32</sup>

In addition, the peak chemical industry body for Europe CEFIC, which represents 25 national chemical industry associations, has also made such commitments to sustainable development. CEFIC state that, *'We aim to ensure that our products are safe to man and the environment and are committed to working in partnership with governments and other stakeholders. Such partnerships are crucial to sustainable development and we try to maintain good and open communications with our various stakeholder groups.'*<sup>33</sup> To achieve these goals CEFIC has created the European Technology Platform for Sustainable Chemistry with a mission, *'to contribute to successful, competitive, sustainable EU chemical and associated industries with global business leadership based on technology excellence.'*<sup>34</sup>

The Plastics and Chemicals Industries Association (PACIA), the pre-eminent national body representing Australia's plastics and chemicals manufacturing sector, is developing a 'Sustainability Leadership Framework'<sup>35</sup> in consultation with its members and stakeholders.<sup>36</sup>

The Chemicals industry globally realise that there are significant business opportunities from green chemistry approaches and are now investing in this field. (See Table 11.1)

<sup>30</sup> Anastas, P., Heine, L., Williamson, T. and Bartlett, L. (2000) *Green Engineering*, American Chemical Society, November.

<sup>31</sup> International Council of Chemical Associations (1996) *Sustainable development and the chemical industry*, International Council of Chemical Associations. Available at [http://www.cefic.be/position/icca/pp\\_ic010.htm](http://www.cefic.be/position/icca/pp_ic010.htm). Accessed 12 December 2007.

<sup>32</sup> Chemical Industries Association (2005) *Holding up the mirror: reflections one year on*, CIA sustainable development report 2005, Chemical Industries Association, p4. Available at [www.cia.org.uk/newsite/sustainability/CIASDRReport05.pdf](http://www.cia.org.uk/newsite/sustainability/CIASDRReport05.pdf). Accessed 12 December 2007.

<sup>33</sup> CEFIC (2002) *The chemical industry's contribution*, CEFIC. Available at <http://www.cefic.be/Templates/shwStory.asp?NID=478&HID=55>. Accessed 12 December 2007.

<sup>34</sup> SusChem (2005) *The vision for 2025 and beyond: a European technology platform for sustainable chemistry*, European Technology Platform for Sustainable Chemistry, p1. Available at <http://www.suschem.org/media.php?mId=2170&PHPSESSID=c1a790799e926502147248ec857c1669>. Accessed 12 December 2007.

<sup>35</sup> See Plastics and Chemicals Industries Association (PACIA) – *Sustainability Leadership Framework* at <http://www.pacia.org.au/index.cfm?menuaction=mem&mMid=021&mid=021.026.001>. Accessed 12 April 2008.

<sup>36</sup> Plastics and Chemicals Industries Association (2007) *Sustainability Leadership Framework: Plastics and Chemicals Industry Discussion Paper*, PACIA, Richmond, Victoria. Available at <http://www.pacia.org.au/uploaditems/docs/4.sustdiscpaper.pdf>. Accessed 12 April 2008.

**Table 11.1: Sustainable Business for the Chemicals and Plastics Sector**

Opportunities	A Selection of World Class Examples and Reports.
<b>Plastic Recycling</b>	PACIA plastic recycling members <sup>37</sup> have already achieved remarkable results and innovations in recycling. Pot Recyclers, <sup>38</sup> Close the Loop <sup>39</sup> and Repeat Products for instance have achieved significant innovations. The work of plastic recycling experts like Dr John Scheirs shows that it is possible to achieve a sustainable plastics industry in Australia. While not all plastics can be recycled, advances in design for recycling and pyrolysis (thermalysis) mean that it is possible to close the loop and achieve virtually no plastic waste to landfill. <sup>40</sup>
<b>Turning Cost Centres into Profit Centres</b>	The costs of complying with the regulations that deal with environmental problems through remediation activities (i.e. waste treatment, control, and disposal costs) rather than prevention methods add significant costs to business. Solutions for bypassing the environmental and economic hurdles associated with waste treatment and disposal in the chemicals industry are now an increasingly high priority. The objective is to be 'benign by design' through green chemistry and green engineering. Australia has leading expertise in this area at for instance the Monash University Green Chemistry Institute. Leading international companies are now reporting their experiences of implementing green chemistry to dramatically reduce the use of toxic chemicals. <sup>41</sup>
<b>Cleaning up cost effectively</b>	Hazardous waste dumps can now be cleaned up through using a series of microbes, mushrooms and earthworms - and the end-products are toxin-free potting soils. For instance, consider vinyl chloride which is one of the top ten produced chemicals in the world. In 2004, scientists reported in <i>Nature</i> <sup>42</sup> that they have found a microbe that will convert vinyl chloride into an inert substance. Professor Loeffler has already tested the bacterium on vinyl chloride at many contaminated sites in the USA to prove its effectiveness. The bacterium's ability to eat the toxic compound - and render it harmless - was hastened in one test by adding plant fertilizer and other nutrients to the soil. <i>'These organisms can only grow when the contaminants are present,'</i> Loeffler said. <i>'When the material is gone, their numbers decline because they don't have any food. So really it's a perfect system.'</i> <sup>43</sup>
<b>Renewable Feedstocks</b>	Kenaf is an example of a extremely fast growing plant that absorbs more CO <sub>2</sub> than almost any other crop. NEC uses its chemicals to reinforce polylactic acid and produce a superior plastic. The resulting bioplastic is biodegradable. Its superior strength and heat resistance will allow its use in electronic products. <sup>44</sup>

### **Creating Chemicals from Renewable Feedstocks**

The transition to sustainable development will likely include replacing raw materials from non-renewable sources with renewable resources, through the recycling of chemicals and biomass. Here the aim is replacing existing industrial feedstocks (which tend to be hazardous and are generally derived from non-renewable resources such as petroleum), with non-toxic, renewable or biologically derived materials.

<sup>37</sup> See PACIA - Plastic Recycling Company Members at [www.pacia.org.au/index.cfm?menuaction=mem&mmid=016&mid=016.001.006](http://www.pacia.org.au/index.cfm?menuaction=mem&mmid=016&mid=016.001.006). Accessed 12 December 2007.

<sup>38</sup> See Pot Recyclers website at [http://www.potrecyclers.com/about\\_us.html](http://www.potrecyclers.com/about_us.html). Accessed 12 December 2007.

<sup>39</sup> See Close the Loop website at <http://www.closesthe-loop.com.au/aboutus/index.htm>. Accessed 12 December 2007.

<sup>40</sup> Scheirs, J. and Morriss. S (2005) *Closing the Loop on Plastics Recycling in Australia - The Challenge*, private correspondence to the authors.

<sup>41</sup> Greiner, T., Rossi, M., Thorpe, B. and Kerr, B. (2006) *Healthy business strategies for transforming the toxic chemicals economy*, Clean Production Action. Available at <http://www.cleanproduction.org/library/CPA-HealthyBusiness-1.pdf>. Accessed 9 September 2007.

<sup>42</sup> He, J., Loeffler, F. and Ritalahti, K. (2003) 'Detoxification of Vinyl Chloride to Ethene Coupled to Growth of an Anaerobic Bacterium', *Nature*, Vol. 424, pp62-65.

<sup>43</sup> Ibid.

<sup>44</sup> See NEC - NEC develops a new bioplastic Available at [www.prdomain.com/companies/NEC/newsreleases/20074940118.htm](http://www.prdomain.com/companies/NEC/newsreleases/20074940118.htm)

Accessed 12 December 2008 .

Many would be sceptical that the planet could provide enough biomass to enable a shift 'off oil' to sourcing chemical feedstocks entirely from biomass. Yet the first major national research project to investigate these issues found that this was indeed possible. The Netherlands Government's 5-year Sustainable Technology Development (STD) project found that, in principle, there is sufficient biomass production potential to meet the demands for industrial organic chemicals, after the more pressing needs to produce food have been met.<sup>45</sup> And they have set about working out how exactly this can be done. Netherlands imports most of its oil and petroleum products and hence will need to restructure its chemical industry this century one way or another. The work of the Netherlands STD project found that, '*practically all the major commodity products of the synthetic organic industrial chemicals sector can be produced, in principle from plant materials.*'<sup>46</sup>

The restructuring of raw materials is not new to the chemical industry. There have been several earlier transformations that have arisen from shifts in basic feedstock. When coal was the main raw material source, acetylene and aromatics were the main starting compounds in the production chain of organic chemicals for industry and pharmaceuticals. Whole families of chemicals were derived from them. When coal gave way to oil, ethylene and benzene replaced these as starting compounds. A comparable transition can be envisaged in respect to a shift from oil to biomass. In this case, the starting compounds of the future could be hydrogen, carbon monoxide, synthesis gas, methanol, furfural, glucose and adipic acid. Presently, these renewable chemical feedstocks meet niche markets in the overall chemical feedstock market, but to truly shift to a sustainable chemicals industry most of the chemicals currently used need to be produced from renewable feedstocks. Table 11.2 shows possible uses for renewable feedstocks currently grown in the US.

**Table 11.2.** Illustrative industrial uses for oil crops in the USA

Renewable Oil Crop	Some Main Uses
<b>Bladderpod</b>	Plastics, fatty acids, surfactants
<b>Buffalo Ground</b>	Epoxy fatty acids, resins, paints, adhesives.
<b>Castor</b>	Dyes, paints, varnishes, bio-pesticides
<b>Coconut</b>	Polymer resins, cosmetics, pharmaceuticals
<b>Corn/Maize</b>	Fermentation products
<b>Crambe</b>	Paints, industrial nylon, lubricants, plastics
<b>Cuphac</b>	Surfactants, lubricants, glycerine
<b>Euphorbia</b>	Surfactants, lubricants, paints, cosmetics
<b>Honesty</b>	Plastics, foam suppressers, lubricants
<b>Jojoba</b>	Cosmetics, pharmaceuticals, inks, plastics
<b>Lesquella</b>	Paints, lubricants, hydraulic fluids, cosmetics.
<b>Linseed</b>	Drying Oils, paints, varnishes, inks
<b>Meadowfoam</b>	Cosmetics, liquid wax, lubricants, rubber
<b>Oil Palm</b>	Fermentation products, soap, wax
<b>Rapeseed</b>	Plastics, foam suppressants, lubricants
<b>Safflower</b>	Paints, varnishes, fatty acids, adhesives
<b>Soybean</b>	Inks, paint solvents, plasticisers, resins
<b>Stokes Astor</b>	Plastic resins, plasticiers, paints
<b>Sunflower</b>	Plasticiers, Fuel Additives, Agrochemicals

<sup>45</sup> Okkerse, C. and Van Bekkum, H. (1996) 'Renewable Raw Materials for the Chemicals Industry' in *Sustainability and Chemistry*. Research paper for the Sustainable Technology Development Project, Delft, Netherlands.

<sup>46</sup> Weaver, P., Jansen, L., van Grootveld, G., van Spiegel, E. and Vergragt, P. (2000) *Sustainable Technology Development*, Greenleaf Publishing, Sheffield, UK, Chapter 10, pp231-246.

Renewable Oil Crop	Some Main Uses
Vermonia	Plastics, alkyd paints, epoxy fatty acids

Source: Moser (1998); USOTA (1992); Robbelen *et al.* (1991)<sup>47</sup>

Already plant derived chemicals make up a significant percentage of the USA chemicals market. The main barrier to further penetration of the market appears to be cost barriers. Table 11.3 shows that those plant derived chemicals which are cost competitive have already claimed around 50 per cent of the market. This shows that once cost barriers are overcome chemicals from renewable feedstocks can compete very well against chemicals derived from petroleum.

**Table 11.3.** Estimated output volumes and market shares of plant-derived products in the US

Product	Total Production (tons)	Plant Derived (tons)	Cost (total) (US\$/kg)	Cost (Plant Derived) (US\$/kg)	Plant Derived Market Share (%)
Plastics	30.0	1.5	0.5	4.0	4.3
Pigments	15.0	1.4	2.0	5.8	9.0
Detergents	12.6	2.3	1.1	1.7	18.0
Wall Paints	7.8	0.7	0.5	1.2	9.0
Adhesives	5.0	2.4	1.6	1.4	48.0
Dyes	4.5	0.8	12.0	21.0	15.0
Surfactants	3.5	1.8	0.5	0.5	50.0
Inks	3.5	0.6	2.0	2.5	16.0

Source: Moser (1998); USOTA (1992)<sup>48</sup>

## ***Benign by Design – Case Studies of Good Practice***

### **Case Study 1: MacDonough-Braungart Design Chemistry**

The McDonough-Braungart Design Chemistry Group (MBDC) are working with many of the US Fortune 500 companies to implement green chemistry, including Nike, BASF, Volvo, and the City of Chicago. Bill McDonough and Michael Brangart argue that it is time for effective designs that are in harmony with nature and based in green chemistry type principles. McDonough and Braungart call their approach 'Cradle to Cradle', as Bill McDonough explains,

*Cradle-to-cradle design (which aligns with the principles of green chemistry and green engineering) offers hope for an entirely different world. Cradle-to-cradle design begins with*

<sup>47</sup> Moser (1998) 'Ecological Process Engineering: The Potential of BioProcessing', in Ayres, R. and Weaver, P. (eds) *Ecorestructuring: Implications for Sustainable Development*, United Nations University Press, Tokyo; USOTA (United States Office of Technology Assessment) (1992) 'Agricultural Commodities as Industrial Raw Materials', *Chemical Marketing Recorder*, 9 March 1992; Robbelen, G. *et al* (ed) (1991) *Oil Crops in the World*, McGraw-Hill, New York cited in Weaver, P., Jansen, L., van Grootveld, G., van Spiegel, E. and Vergragt, P. (2000) *Sustainable technology development*, Greenleaf Publishing, Sheffield, UK Chapter 10: Elaborating and Evaluating Opportunities: The Case for Organic Materials.

<sup>48</sup> Moser (1998) 'Ecological Process Engineering: The Potential of BioProcessing', in Ayres, R. and Weaver, P. (eds) *Ecorestructuring: Implications for Sustainable Development*, United Nations University Press, Tokyo; USOTA (United States Office of Technology Assessment) (1992) 'Agricultural Commodities as Industrial Raw Materials', *Chemical Marketing Recorder*, 9 March 1992 cited in Weaver, P., Jansen, L., van Grootveld, G., van Spiegel, E. and Vergragt, P. (2000) *Sustainable technology development*, Greenleaf Publishing, Sheffield, UK, Chapter 10: Elaborating and Evaluating Opportunities: The Case for Organic Materials.

*the proposition that the effective, regenerative cycles of nature – the cyclical flows of energy, water and nutrients that support life – provide an unmatched model for wholly positive human designs. In the natural world, one organism's 'waste' cycles through an ecosystem to provide nourishment for other living things; its productivity is beneficial and regenerative – waste equals food. Just so, cradle-to-cradle products are designed to circulate in closed-loop cycles that virtually eliminate waste and provide 'nutrients' for nature and industry. The cradle-to-cradle framework developed by my colleague Michael Braungart and myself recognizes two metabolisms within which materials flow as healthy nutrients. First, nature's nutrient cycles constitute the biological metabolism. Materials designed to flow optimally in the biological metabolism are biological nutrients. Products conceived as these nutrients, such as biodegradable fabrics, are designed to be used and safely returned to the environment to nourish living systems. Second, the technical metabolism, designed to mirror earth's cradle-to-cradle cycles, is a closed-loop system in which valuable, high-tech synthetics and mineral resources – technical nutrients – circulate in perpetual cycles of production, recovery and remanufacture. Ideally, all the human artefacts that make up the technical metabolism, from buildings to manufacturing systems, are powered by renewable energy. Working within this framework we can, by design, enhance humanity's positive impact on the world. Rather than limiting growth or reducing emissions or using brute force to overcome the rules of the natural world, we can create economies worldwide that purify air, land and water; that rely on current solar income and generate no waste; that support energy-effectiveness, healthy productivity and social well-being. In short, sound, regenerative economies that enhance all life.*

McDonough illustrates their cradle to cradle methodology with the following example:

*In 1993, we helped to conceive and create a compostable upholstery fabric, a biological nutrient. We were initially asked by Design Tex to create an aesthetically unique fabric that was also ecologically intelligent, although the client did not quite know at that point what this would (tangibly) mean. The challenge helped to clarify, both for us and for the company we were working with, the difference between superficial responses such as recycling and reduction and the more significant changes required by the Next Industrial Revolution. For example, when the company first sought to meet our desire for an environmentally safe fabric, it presented what it thought was a wholesome option: cotton, which is natural, combined with PET (Polyethylene Terephthalate) fibres from recycled beverage bottles. Since the proposed hybrid could be described with two important ecobuzzwords, 'natural' and 'recycled,' it appeared to be environmentally ideal. The materials were readily available, market-tested, durable, and cheap. But when the project team looked carefully at what the manifestations of such a hybrid might be in the long run, we discovered some disturbing facts. When a person sits in an office chair and shifts around, the fabric beneath him or her abrades; tiny particles of it are inhaled or swallowed by the user and other people nearby. PET was not designed to be inhaled. Furthermore, PET would prevent the proposed hybrid from going back into the soil safely, and the cotton would prevent it from re-entering an industrial cycle. The hybrid would still add junk to landfills, and it might also be dangerous.*

*The team decided to design a fabric so safe that one could literally eat it. The European textile mill chosen to produce the fabric was quite 'clean' environmentally, and yet it had an interesting problem: although the mill's director had been diligent about reducing levels of dangerous emissions, government regulators had recently defined the trimmings of his*

*fabric as hazardous waste. We sought a different end for our trimmings: mulch for the local garden club. When removed from the frame after the chair's useful life and tossed onto the ground to mingle with sun, water and hungry micro-organisms, both the fabric and its trimmings would decompose naturally. The team decided on a mixture of safe, pesticide-free plant and animal fibres for the fabric (ramie and wool) and began working on perhaps the most difficult aspect: the finishes, dyes, and other processing chemicals. If the fabric was to go back into the soil safely, it had to be free of mutagens, carcinogens, heavy metals, endocrine disrupters, persistent toxic substances and bio-accumulative substances. Sixty chemical companies were approached about joining the project, and all declined, uncomfortable with the idea of exposing their chemistry to the kind of scrutiny necessary. Finally one European company, Ciba-Geigy, agreed to join. With that company's help the project team considered more than 8000 chemicals used in the textile industry and eliminated 7962. The fabric – in fact, an entire line of fabrics – was created using only 38 chemicals. The resulting fabric has garnered gold medals and design awards and has proved to be tremendously successful in the marketplace. The non-toxic fabric, Climatex®Lifecycle™, is so safe that the fabric's trimmings can indeed be used as a mulch by local garden clubs. The director of the mill told a surprising story after the fabrics were in production. When regulators came to test the effluent, they thought their instruments were broken. After testing the influent as well, they realized that the equipment was fine – the water coming out of the factory was as clean as the water going in. The manufacturing process itself was filtering the water. The new design not only bypassed the traditional three-R responses to environmental problems but also eliminated the need for regulation.<sup>49</sup>*

## Case Study 2: Argonne National Lab, USA

Leading research institutions now have green chemistry research programs. This is helping to advance knowledge rapidly and create new ways for industry to reduce toxic chemical usage. An excellent example of green chemistry is the technology developed by Argonne National Lab, a winner of the 1998 USA President's Awards for Green Chemistry.<sup>50</sup>

Every year in the United States alone, an estimated 3.5 million tons of highly toxic, petroleum-based solvents are used as cleaners, degreasers, and ingredients in adhesives, paints, inks, and many other applications. More environmentally friendly solvents have existed for years, but their higher costs have perhaps kept them from wide use.

A technology developed by Argonne National Labs produces non-toxic, environmentally friendly 'green solvents' from renewable carbohydrate feedstocks, such as corn starch. This discovery has the potential to replace about 80 per cent of petroleum-derived cleaners, degreasers and other toxic and hazardous solvents. The process makes low-cost, high-purity ester-based solvents, such as ethyl lactate, using advanced fermentation, membrane separation, and chemical conversion technologies. These processes require very little energy and eliminate the large volumes of waste salts produced by conventional methods. This method of producing biodegradable ethyl lactate solvents can also cut the price by up to 50 per cent, from US\$1.60 - \$2.00 per pound to less than US \$1.00 per pound. Overall, the process uses as much as 90 per

<sup>49</sup> McDonough, W. and Braungart, M. (2002) *Cradle to Cradle: Remaking the Way We Make Things*, North Point Press, NY.

<sup>50</sup> See US EPA Presidential Green Chemistry Awards - 1998 Greener Reaction Conditions Award at <http://epa.gov/greenchemistry/pubs/pgcc/winners/grca98.html>. Accessed 3 January 2007; See Argonne National Laboratory - Ethyl Lactate Solvents at [http://www.anl.gov/techtransfer/Available\\_Technologies/Environmental\\_Research/ethylactate.html](http://www.anl.gov/techtransfer/Available_Technologies/Environmental_Research/ethylactate.html). Accessed 3 January 2007.



cent less energy and produces ester lactates at about 50 per cent of the cost of conventional methods. The lactate esters from this process can also be used as 'platform' building blocks to produce polymers and large-volume biodegradable oxy-chemicals, such as propylene glycol and acrylic acid. Markets for these biodegradable polymers and oxy-chemicals might soon surpass those of green solvents.

### Leading Green Chemistry Award Winners

The case studies listed above have received the US Presidential Green Chemistry Challenge Awards, which recognise individual researchers. Table 11.4 provides some other examples.<sup>51</sup>

**Table 11.4** A selection of award winners from the US Presidential Green Chemistry Awards

Company	Sample of USA Presidential Green Chemistry Awards
Professor Galen J. Suppes, University of Missouri-Columbia <b>2006 Academic Award</b>	For the invention of a system of converting waste glycerine from bio-diesel production to propylene glycol. Professor Suppes enabled conversion to occur at a significantly lower temperature using a copper-chromite catalyst, while raising the efficiency of the distillation reaction. Propylene glycol produced through this method is cost competitive enough to replace the more toxic ethylene glycol, the primary ingredient in automobile anti-freeze. <sup>52</sup>
ADM and Novozymes <b>2005 Greener Synthetic Pathways Award</b>	Medical research has shown the negative effects on human health of Trans-fats. Novozymes and ADM have worked together to develop techniques that do not create Trans-fats. They have developed a new green process for the esterification of oils and fats which interchanges saturated and unsaturated fatty acids without producing Trans-fats. As well as providing significant health benefits the process has greatly improved the atom economy, reduced the use of toxic chemicals and water, and waste by-products. <sup>53</sup>
<b>Engelhard Organic Pigments</b> 2004 Designing Safer Chemicals Award	Red, orange and yellow pigments historically were created using toxic heavy metals such as lead, chromium and cadmium. Engelhard developed environmentally friendly 'Rightfit' pigments for use in packaging and has a plan to phase out its use of heavy metals. In addition, a water-based manufacturing process was developed to replace the organic solvents usually associated with the creation of pigments. <sup>54</sup>
<b>Bristol-Myers Squibb Co.</b> 2004 Alternative Synthetic Pathways Award	The anti-cancer drug Taxol was first isolated from the bark of the Pacific yew tree, but isolating it required stripping the bark from the trees, killing them in the process. In addition, producing the drug took more than 20 chemical steps requiring some 20 solvents and reagents. Bristol-Myers Squibb developed a way to grow cell lines from yew trees in large fermentation tanks using only water, sugars, vitamins and trace elements. During its first five years, the process is expected to eliminate an estimated 32 metric tons of hazardous chemicals and other materials. <sup>55</sup>
Buckman Laboratories International <b>2004 Alternative Solvents/Reaction Conditions Award</b>	One-half of the paper and paperboard currently used in the USA is recycled, but adhesives, coatings, plastics and other materials on the old paper can produce spots and holes in the new paper. Called 'stickies', they cost the industry US\$500 million annually. Buckman uses a new enzyme to turn stickies into a water-soluble, non-sticky material. The enzyme is produced by bacteria and is completely bio-degradable. Since 2002, more than 40 paper mills have converted to the enzyme. <sup>56</sup>

<sup>51</sup> See US EPA - Presidential Green Chemistry Challenge at <http://www.epa.gov/greenchemistry/pubs/pgcc/presgcc.html>. Accessed 5 January 2007.

<sup>52</sup> See US EPA - 2006 USA Presidential Green Chemistry Challenge at <http://www.epa.gov/greenchemistry/pubs/pgcc/past.html>. Accessed 5 January 2007.

<sup>53</sup> See US EPA - Presidential Green Chemistry Challenge 1996-2006 at <http://www.epa.gov/greenchemistry/pubs/pgcc/presgcc.html>. Accessed 5 January 2007.

<sup>54</sup> See US EPA - 2004 Presidential Green Chemistry Challenge at <http://www.epa.gov/greenchemistry/pubs/pgcc/past.html#2004>. Accessed 5 January 2007.

<sup>55</sup> Ibid.

<sup>56</sup> Ibid.

Source: US EPA<sup>57</sup>

In addition, there are a number of other awards internationally, in Canada,<sup>58</sup> Australia,<sup>59</sup> Japan,<sup>60</sup> and the United Kingdom.<sup>61</sup> In 2005, the Nobel Prize Committee acknowledged the importance of Green Chemistry by awarding the Nobel Prize for Chemistry for *'the development of the metathesis method in organic synthesis'* to Yves Chauvin, Robert H. Grubbs, and Richard R. Schrock. The Nobel Prize Committee wrote that, *"This represents a great step forward for 'green chemistry', reducing potentially hazardous waste through smarter production. Metathesis is an example of how important basic science has been applied for the benefit of man, society and the environment"*.<sup>62</sup>

<sup>57</sup> See US EPA - *Presidential Green Chemistry Challenge 1996-2006* at <http://www.epa.gov/greenchemistry/pubs/pgcc/presgcc.html>. Accessed 5 January 2007.

<sup>58</sup> See Canadian Green Chemistry Network - *CGCN Homepage* at <http://www.greenchemistry.ca/>. Accessed 5 January 2007.

<sup>59</sup> See The Royal Australian Green Chemistry Institute - *Australia's Green Chemistry Challenge Awards* at <http://www.raci.org.au/national/awards/greenchemistry.html>. Accessed 5 January 2007.

<sup>60</sup> See The Green & Sustainable Chemistry Network - *Awards* at <http://www.gscn.net/awardsE/index.html>. Accessed 5 January 2007.

<sup>61</sup> See Green Chemistry Network - *2005 Crystal Faraday Green Chemical Technology Awards* at <http://www.chemsoc.org/networks/gcn/awards.htm>. Accessed 5 January 2007.

<sup>62</sup> The Nobel Foundation (2006) 'Press Release: The Nobel Prize in Chemistry 2005', Press Release, The Nobel Foundation. Available at [http://nobelprize.org/nobel\\_prizes/chemistry/laureates/2005/press.html](http://nobelprize.org/nobel_prizes/chemistry/laureates/2005/press.html). Accessed 3 November 2008.

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