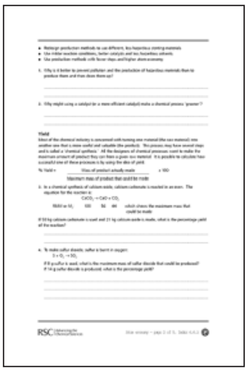
Green Chemistry, atom economy and sustainable development



Index 6.6.1
5 sheets

The competing needs of development and environmental protection are often mentioned in the media and many students have opinions on the subject. Chemistry is seen as a 'polluter,' which partly accounts for its poor image among students and the general public. This activity introduces the concept of atom economy in the context of sustainable development and Green Chemistry. It aims to show that development is necessary but can be achieved in a way which limits environmental damage.

Prior knowledge required

Students need to know/be able to:

- Calculate relative molecular mass (RMM or M_r)
- Know what a reversible reaction is and how the yield of a reaction might be affected by its reversible nature
- Calculate percentage yield – a section on this is included in the resource but it would be better if students had already covered it so that they do not get it mixed up with atom economy.

Further information

Further information on sustainable development is available on various websites, including:

http://www.uyseg.org/sustain-ed/Index.htm – this website of the Chemical Industry Education Centre is a good introduction to why development is necessary and how it can be made more sustainable. Students can calculate their personal sustainability and also how much carbon dioxide they produce in a year. Examples of chemical industries that are going greener are provided, along with links to several other sites. This could provide a useful basis for some project-type work on the topic.

http://www.uyseg.org/greener_industry/index.htm – the Chemical Industry Association's Greener Industry website. There is an interesting section on greener cars, as well as information on other areas of chemical industry.

http://www.makepovertyhistory.org/schools/resources.shtml – this page from Make Poverty History has a list of resources on the topic of development that are available

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free to schools, mainly from various charities working in the developing world. These are not specifically chemistry-based resources (and most, if not all, do not mention chemistry at all) but they may provide good background material on the need for development.

http://www.chemsoc.org/networks/learnnet/green/index.htm – this is a resource from the Royal Society of Chemistry and is mainly aimed at post-16s, but the site contains some interesting information and further details about atom economy and Green Chemistry.

(All sites accessed December 2005.)

Answers

1. Various answers are possible, including: not all pollution may be cleared up; energy will be wasted producing unwanted products; it is better not to produce hazardous materials at all then there is no danger of them being spilled or falling into the wrong hands.

2. Using a catalyst (or more efficient catalyst) may mean that the process can be carried out at a lower temperature, which saves energy. (It may also increase the yield of one product over that of another, unwanted one.)

3. Percentage yield = 21/28 x 100 = 75%

4. Maximum mass of SO_2 that could be produced = 16 g

Percentage yield = 14/16 x 100 = 87.5%

5. Atom economy = 100%

6. Atom economy = 224/356 x 100 = 63%

7. **a)** Displacement = 48/128 x 100 = 37.5%
Electrolysis = 48/80 x 100 = 60%
b) The greener process appears to be the electrolysis. Before finally deciding it might be important to know how much energy is used in each process, what (if any) solvents are used and what the yield is for each reaction.
c) 100 %

8. **a)** Atom economy = 28/142 = 20%
b) Atom economy = 142/142 = 100%
c) If only one product can be sold then the rest is wasted; if both can be sold then there is no waste product and the atom economy is greater.

9. **a)** Atom economy = 100%
b) The reversible reaction symbol ($\rightleftharpoons$) suggests that the reaction is unlikely to have a very high yield.

10. Answers may include: more efficient use of resources; less waste; less pollution; less energy used. These things are important for sustainable development because they all help to ensure that we leave the planet healthy for future generations and do not use up all the available resources.

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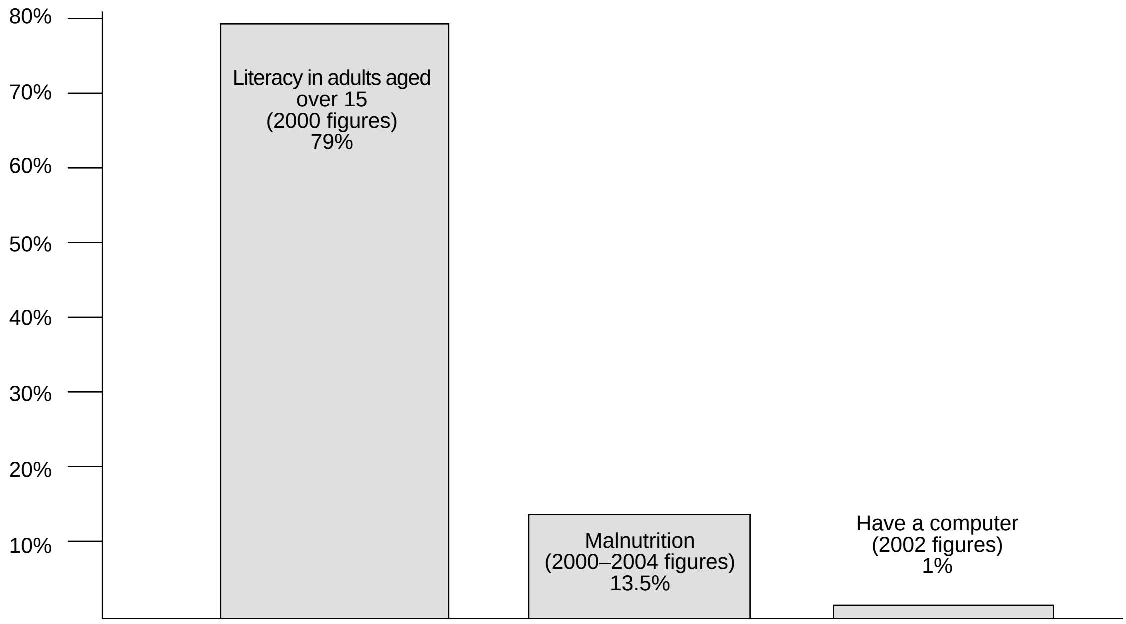

For every 100 people on earth... development statistics taken from the World Bank database of indicators at **http://devdata.worldbank.org./quer/default.htm** and the UN Food and Agriculture organization website **http://www.fao.org/docrep/007/y5650e/y5650e06.htm**

A quarter of the world's people have to survive on less than 70p a day. Millions have no health care and the world's population is expected to increase by about another 3 billion over the next 50 years. Even in developed nations, poverty, education and healthcare could be improved.

To help deal with this situation, the world's economy needs to grow; in particular, the economies of developing nations need to expand. However, economic growth is often linked to environmental pollution problems. The challenge is to develop in a way that meets the needs of the present generation without compromising the ability of future generations to meet their own needs – in other words, without causing a lot of environmental damage and wasting limited resources. This type of development is called 'sustainable development' and it will be more and more critical as the population of the world increases.

One of the ways in which the chemical industry is working towards sustainable development is by using 'Green Chemistry.' One of the basic ideas of Green Chemistry is to prevent pollution and the production of hazardous materials instead of producing them and then cleaning them up. This means that Green Chemistry:

- Is safe
- Conserves raw materials and energy
- Is more cost effective than conventional methods.

There are three main ways to make chemical processes 'greener':

- Redesign production methods to use different, less hazardous starting materials
- Use milder reaction conditions, better catalysts and less hazardous solvents
- Use production methods with fewer steps and higher atom economy.

1. Why is it better to prevent pollution and the production of hazardous materials than to produce them and then clean them up?

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2. Why might using a catalyst (or a more efficient catalyst) make a chemical process 'greener'?

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Yield

Most of the chemical industry is concerned with turning one material (the raw material) into another one that is more useful and valuable (the product). This process may have several steps and is called a 'chemical synthesis.' All the designers of chemical processes want to make the maximum amount of product they can from a given raw material. It is possible to calculate how successful one of these processes is by using the idea of yield.

$$\% \text{ Yield} = \frac{\text{Mass of product actually made}}{\text{Maximum mass of product that could be made}} \times 100$$

3. In a chemical synthesis of calcium oxide, calcium carbonate is roasted in an oven. The equation for the reaction is:

$$CaCO_3 \rightarrow CaO + CO_2$$

RMM or M_r: 100 56 44 which shows the maximum mass that could be made

If 50 kg calcium carbonate is used and 21 kg calcium oxide is made, what is the percentage yield of the reaction?

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4. To make sulfur dioxide, sulfur is burnt in oxygen:

$$S + O_2 \rightarrow SO_2$$

If 8 g sulfur is used, what is the maximum mass of sulfur dioxide that could be produced?
If 14 g sulfur dioxide is produced, what is the percentage yield?

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Atom economy

The idea of yield is useful, but from a Green Chemistry and sustainable development perspective, it is not the full picture. This is because yield is calculated by considering only one reactant and one product. One of the key principles of Green Chemistry is that processes should be designed so that the maximum amount of all the raw materials ends up in the product and a minimum amount of waste is produced. A reaction can have a high percentage yield but also make a lot of waste product. This kind of reaction has a low atom economy. Both the yield and the atom economy have to be taken into account when designing a green chemical process.

Look again at the reaction you considered in Q3:

$$CaCO_3 \rightarrow CaO + CO_2$$

RMM or M_r: 100 56 44

If we split up the formulae, we can look at what happens to each atom in the reaction. The atoms shown below in bold end up in the product we want, the rest do not:

Ca C **O** O O → Ca O + C O O

Waste box
1C
2O

From the original atoms, one C atom and two O atoms are wasted – they are not in the final, useful product.

Green chemists define atom economy as:

$$\% \text{ Atom economy} = \frac{\text{Mass of wanted product(s)} \times 100}{\text{Total mass of products}}$$

So for this example,

$$\% \text{ Atom economy} = \frac{56 \times 100}{100} = 56\%$$

Step-by-step: How to calculate atom economy

Step 1. Write out the balanced equation.

Step 2. Calculate the relative molecular mass of each of the products.

Step 3. Calculate the total mass of all the products (remember to account for any numbers in front of the symbols, eg $2\ Fe_2O_3 + 3\ C \rightarrow 4\ Fe + 3\ CO_2$).

Step 4. Work out which of the products are wanted and calculate their mass (again, do not forget any numbers in front of the symbols).

Apply the formula:

$$\% \text{ Atom economy} = \frac{\text{Mass of wanted product(s)} \times 100}{\text{Total mass of products}}$$

5. Calculate the atom economy for the reaction in Q4.

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6. Iron is extracted from its ore using carbon:

$2\ Fe_2O_3 + 3\ C \rightarrow 4\ Fe + 3\ CO_2$

What is the atom economy of this reaction?

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7. Titanium can be extracted from its ore by two different methods. One uses a more reactive metal to displace the titanium:

$TiO_2 + 2\ Mg \rightarrow Ti + 2\ MgO$

The second method is electrolysis of the ore. The overall reaction for this method is:

$TiO_2 \rightarrow Ti + O_2$

a) Calculate the atom economy for each reaction.

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b) Which method is 'greener'? What else might you want to know before making a final decision?

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c) Oxygen is a useful product and can be sold. What is the atom economy of the electrolysis if the oxygen is collected and sold?

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8. Alkanes can be cracked to form alkenes. Decane can be cracked to form two products:

$C_{10}H_{22} \rightarrow C_2H_4 + C_8H_{18}$

a) If only the alkene can be sold, what is the atom economy of this process?

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b) If both products can be sold, what is the atom economy?

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c) Explain why your answers to (a) and (b) are different.

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9. The key reaction in the Haber process for making ammonia is:

$N_2 + 3H_2 \rightleftharpoons 2NH_3$

a) What is the atom economy of this reaction? (You should not need to do a calculation.)

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b) What does the symbol $\rightleftharpoons$ suggest about the likely yield of this reaction?

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10. Explain why using reactions with high atom economy is important for sustainable development.

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