B.6 Biochemistry and the environment

Understandings

- Xenobiotics refers to chemicals that are found in an organism that are not normally present there.
- Biodegradable/compostable plastics can be consumed or broken down by bacteria or other living organisms.
- Host–guest chemistry involves the creation of synthetic host molecules that mimic some of the actions performed by enzymes in cells, by selectively binding to specific guest species such as toxic materials in the environment.
- Enzymes have been developed to help in the breakdown of oil spills and other industrial wastes.
- Enzymes in biological detergents can improve energy efficiency by enabling effective cleaning at lower temperatures.
- Biomagnification is the increase in concentration of a substance in a food chain.
- Green chemistry, also called sustainable chemistry, is an approach to chemical research and engineering that seeks to minimize the production and release of hazardous chemicals to the environment.

Applications and skills

- Discussion of the increasing problem of xenobiotics such as antibiotics in sewage treatment plants.
- Description of the role of starch in biodegradable plastics.
- Application of host–guest chemistry to the removal of a specific pollutant in the environment.
- Description of an example of biomagnification, including the chemical source of the substance. Examples could include heavy metals or pesticides.
- Discussion of the challenges and criteria in assessing the "greenness" of a substance used in biochemical research, including the atom economy.

Nature of science

- Risk assessment, collaboration, ethical considerations – it is the responsibility of scientists to consider the ways in which products of their research and findings negatively impact the environment, and to find ways to counter this. For example, the use of enzymes in biological detergents, to break up oil spills, and green chemistry in general.

The nature of biochemistry

Biochemistry is a multidisciplinary science that studies the chemical changes associated with living organisms and their interactions with the environment. Our increasing understanding of biochemical processes has greatly enhanced our ability to control biological systems but at the same time created serious ecological problems and raised our awareness of the environmental and ethical implications of science and technology. In this topic we shall discuss the use of biochemical techniques in industrial, agricultural, and household applications, their effects on global and local ecosystems, and the role of biochemistry in reducing the environmental impact of human activities.

Risk assessment

Before carrying out an experiment any scientist must estimate the individual, environmental, and ethical implications of the proposed work. This work, known as **risk assessment**, is particularly important when potentially hazardous chemical or biological materials can be released to the environment, cause unnecessary suffering to laboratory animals, or present a significant risk to human health. In each case, the experimenter is responsible for minimizing the negative impact of his or her work and providing a comprehensive list of emergency procedures to counter any accidental damage to the environment or individuals involved in the research.

Xenobiotics

The rapid development of organic chemistry in the twentieth century led to the industrial production of pesticides, medicinal drugs, and other chemical compounds that had no natural sources and therefore were foreign to living organisms. These compounds, known as **xenobiotics**, are generally toxic to various life forms and are more resistant to biodegradation than naturally occurring organic molecules. Certain xenobiotics (**persistent organic pollutants, POPs**) can remain in the soil and in animal fatty tissues for many decades after their release into the environment.

DDT

The abbreviated name of the most notorious insecticide, DDT, is derived from its semi-systematic name, **d**ichloro**d**iphenyl**t**richloroethane (figure 1).

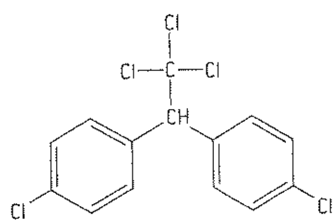


Figure 1 DDT, dichlorodiphenyltrichloroethane

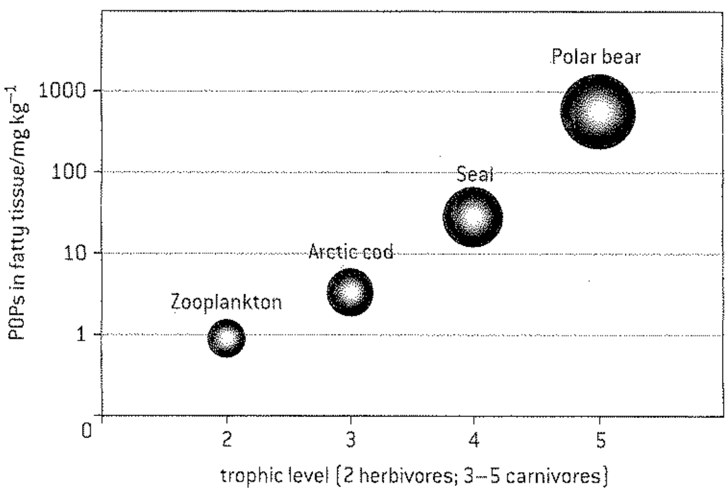
From 1950 to 1980, about 2 million tonnes of DDT were produced and released to the environment worldwide, enabling significant increases in the yields of agricultural crops and nearly eradicating certain diseases such as malaria and dengue fever. However, very soon the widespread use of DDT created resistant insect populations, reducing the effectiveness of this compound and, in many cases, reversing the initial gains in agricultural production and disease control. In addition, it was discovered that DDT was particularly stable in the environment and could accumulate in animals, poisoning wildlife and creating a significant risk to human health. In the 1970s and 1980s this insecticide was banned in most countries, although its limited use is still allowed in regions affected by malaria and other insect-transmitted diseases.

Figure 2 The bald eagle was brought close to extinction by the widespread use of DDT in agriculture. The biomagnification of DDT in these birds of prey led to the thinning of their eggshells, which became too brittle so their chicks could not hatch. Since the ban on DDT introduced in the USA in 1972, the population of bald eagles has increased from several hundred to over 150 000 individuals

The metabolism of xenobiotics

Depending on their chemical structure, some xenobiotics can be completely digested by microorganisms, plants, and animals. However, many synthetic chemicals produce toxic metabolites, alter the metabolic pathways of other compounds, or affect the reproduction, development, and growth of living organisms. Certain xenobiotics cannot be metabolized by existing enzymes (sub-topic B.2) and either remain within the organism or are excreted unchanged.

The nature of its functional groups and the overall polarity of a xenobiotic molecule strongly affects its rate of decomposition in the environment. Polar synthetic chemicals are often soluble in water and are quickly metabolized by living organisms or undergo photochemical oxidation. In contrast, non-polar, hydrophobic xenobiotics easily pass through biological phospholipid membranes (sub-topic B.3) and tend to accumulate within the cells of microorganisms or in fatty tissues of animals. When such compounds are passed along the food chain, their concentrations may increase exponentially and reach very high levels in top predators (figure 3). This process, known as **biomagnification**, has been largely responsible for the extinction or significant population reduction of many birds of prey and large marine animals across the globe, often in regions far distant from the places where the xenobiotics were released to the environment.



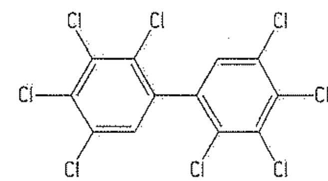
▲ Figure 3 Biomagnification of persistent organic pollutants (POPs) in a food chain

Heavy metal toxicity

Heavy metals, such as mercury, cadmium, and lead, have numerous industrial applications and may be released to the environment at all stages of their production and utilization. These elements cause denaturation of proteins (sub-topic B.2), inhibit the action of enzymes (sub-topic B.7), and affect the redox balance in cells. Although heavy metals are toxic to nearly all living organisms, they often undergo biomagnification and thus are particularly dangerous to predators at the tops of food chains. The environmental impact of heavy metals and common methods of their removal are discussed in sub-topic A.10.

PCBs

Polychlorinated biphenyls (**PCBs**) are synthetic organic molecules containing two benzene rings with some or all hydrogen atoms replaced by chlorine; an example is shown in figure 4.



▲ Figure 4 The structure of a polychlorinated biphenyl (PCB)

These compounds were widely used in the twentieth century as coolants, lubricants, plasticizers, and insulating liquids. PCBs were found to cause cancer and liver damage in animals and humans, so their production in most countries was banned in the 1970s. However, PCBs are still present in the environment in significant quantities. In 1996, 20 years after the ban was introduced, the body of a Beluga whale discovered in the St Lawrence River in Canada contained PCBs in excess of 50 mg kg^{-1}. According to local regulations, the whale was classified as hazardous to the environment and had to be disposed of as toxic chemical waste.

Worked example

Atlantic mackerel is a common prey of porbeagle shark, which consumes about 100 mackerel fish per month. Mercury and other heavy metals from consumed mackerel remain in the shark's body for approximately 2 years. Calculate the concentration of mercury in porbeagle shark if mackerel contains 0.05 ppm of mercury (1 ppm = 10^{-4}%), the mass of an average mackerel is 1 kg, and the mass of a porbeagle shark is 120 kg.

Solution

In 2 years (24 months), the shark consumes 2400 mackerel with a total mass of 2400 kg. The mercury level in mackerel is $0.05 \times 10^{-4}\% = 5 \times 10^{-6}\%$, so the mass of mercury in consumed mackerel is $2400\ \text{kg} \times 5 \times 10^{-6} / 100 = 1.2 \times 10^{-4}$ kg. Therefore, the concentration of mercury in the shark's body is $(1.2 \times 10^{-4}\ \text{kg}/120\ \text{kg}) \times 100\% = 1 \times 10^{-4}\%$, or 1 ppm. As a result of biomagnification, this concentration is 20 times higher than the level of mercury in mackerel.

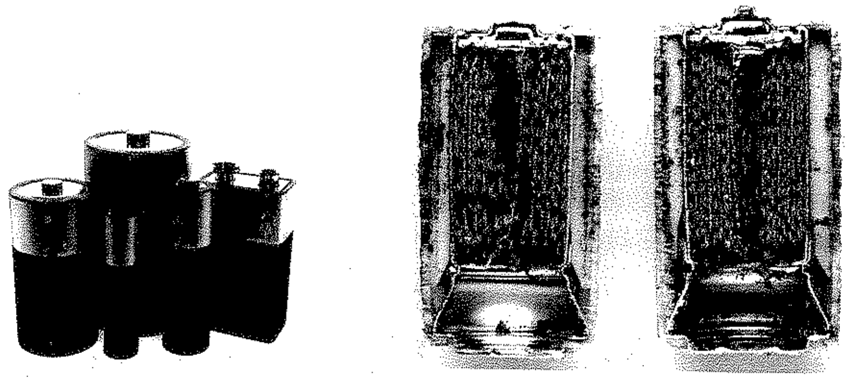


Figure 5 Left: household batteries contain heavy metals and must be recycled to protect the environment. Right: alternating layers of nickel and cadmium in a rechargeable battery

Pharmaceutically active compounds and detergents

Antibiotics and other **pharmaceutically active compounds (PACs)** are a diverse group of xenobiotics commonly found in soil and aquatic ecosystems. At present very little is known about the occurrence, effects, and risks of the release of PACs into the environment. One of the major concerns is the development of resistant bacteria (sub-topics D.3 and D.6), which evolve to survive in the presence of antibiotics and pass their resistance to future generations. Such bacteria may cause serious diseases that cannot be treated effectively by existing medications. In addition, certain PACs affect immune and endocrine systems of aquatic animals, increasing the risk of infectious diseases and inhibiting their reproductive functions.

Another type of common environmental pollutant is household and industrial **detergents** containing amphiphilic molecules (sub-topic B.3) that reduce the surface tension of water and facilitate the cleaning of fabrics and solid surfaces. Many detergents such as *branched alkylbenzenesulfonates* (*ABSs*) have very poor biodegradability and accumulate in sewage treatment plants, producing persistent foam and altering the bacterial composition of recycled water. In developed countries ABSs have been phased out and replaced by biodegradable *linear alkylbenzenesulfonates* (*LASs*), which reduced the levels of surfactants in water and helped to restore the biodiversity of aquatic ecosystems (figure 7, see next page).

Biological detergents contain a variety of enzymes extracted from thermophilic microorganisms. These enzymes facilitate the biological breakdown of fats, proteins, starch, and other organic molecules, providing fast and effective cleaning even in cold water. At the same time, they are more resistant to thermal denaturation (sub-topic B.3) and can be used at temperatures up to 50 °C. Most enzymes used in biological detergents are easily biodegradable and do not have any lasting impact on the environment. In addition, their use saves energy and reduces the amount of non-biological detergents used for cleaning, which is particularly important in densely populated areas with limited capacity of sewage treatment

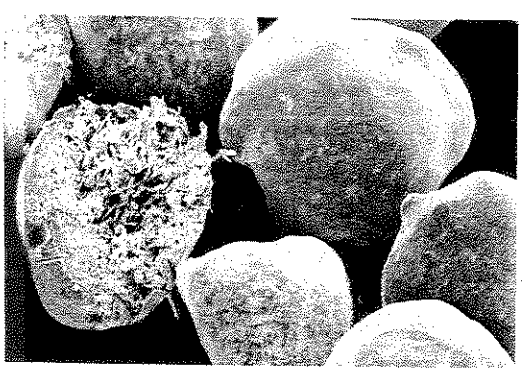
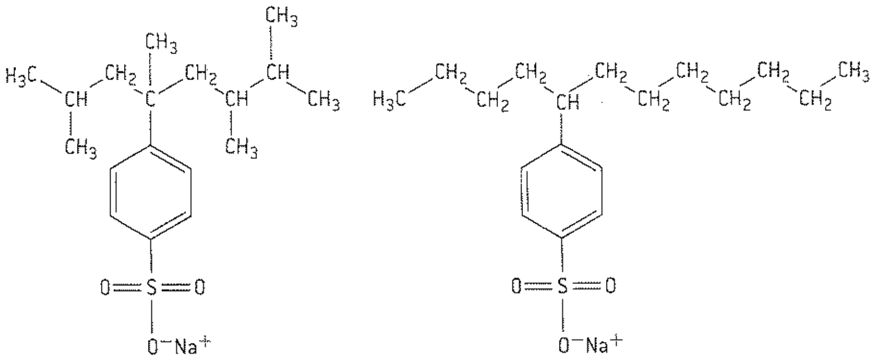
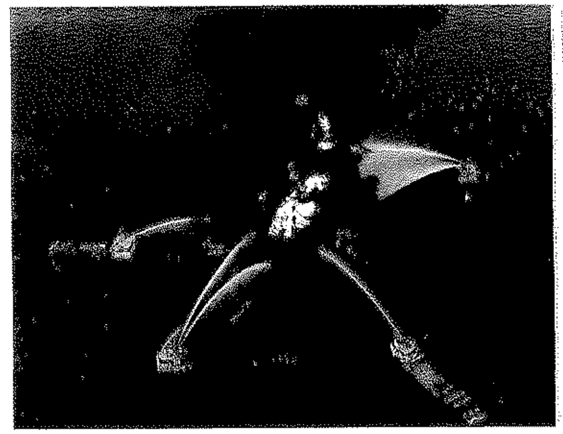


Figure 6 Biological washing powders contain granules of encapsulated enzymes



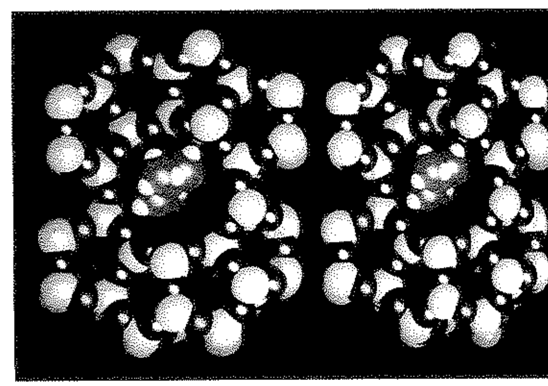
▲ Figure 7 A non-biodegradable branched alkylbenzenesulfonate (ABS) contrasted with a biodegradable linear alkylbenzenesulfonate (LAS)



▲ Figure 8 The Deepwater Horizon disaster in the Gulf of Mexico, 2010

plants. The only known side effect of biological detergents is the possibility of allergic reactions in certain individuals with increased skin sensitivity.

Enzymes and microorganisms are also used to clean up oil spills and industrial wastes. The exact clean-up procedure depends on many factors including the chemical nature and volatility of the waste, location of the spill, temperature, and so on. Generally a mixture of enzymes, surfactants, and other chemicals is used for the initial breakdown of the oil or waste components into biodegradable products, which are further metabolized by common microorganisms. Several strains of oil-degrading bacteria have been discovered near the sites of major oil spills, including the Deepwater Horizon in the Gulf of Mexico, and have been successfully used to break down hydrocarbon-based industrial wastes.



▲ Figure 9 Host–guest complexes of xylene (green and white) with zeolite (yellow and red)

Host–guest complexes

Although enzymatic processes are highly selective and efficient, many enzymes are unstable in the environment and show their optimal activity in narrow ranges of pH and temperature (sub-topic B.2). Certain synthetic molecules are free from these limitations and can selectively bind to environmental pollutants. The resulting **supramolecules**, or **host–guest complexes**, mimic the structures of enzyme–substrate complexes (sub-topic B.2), where the synthetic analogue of the enzyme (**host**) and the environmental pollutant (**guest**) are held together by multiple non-covalent interactions including van der Waals' forces, ionic bonds, and hydrogen bonds (sub-topic 4.4).

To form a stable complex the host and guest molecules must have complementary chemical structures and three-dimensional configurations. In the simplest case the host molecule contains a cavity of a certain size and interacts with a substrate (guest) only by van der Waals' forces. Such host molecules can bind to a broad range of environmental pollutants but have low selectivity and interact with any substances that fit into the cavity. The presence of functional groups that form specific hydrogen or ionic bonds with the substrate increases the

Various host–guest systems have been successfully used for the immobilization and removal of inorganic ions (including heavy metals and radioactive elements such as caesium-137), polychlorinated compounds (PCBs and dioxins), and carcinogenic aromatic amines from water and industrial waste. In addition to environmental applications, host–guest complexes are used in medicine for targeted drug delivery, which is particularly important in cancer treatment.

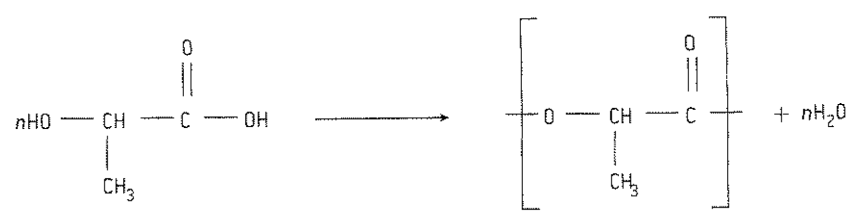
selectivity of host–guest interactions but often makes the host molecule more sensitive to pH and temperature.

In certain cases the function of the host can be performed by microporous solid materials such as zeolites (aluminosilicate minerals) or branched organic polymers. The pollutants immobilized on the surface of the host material can be mechanically separated from the environment for further processing or incineration.

Plastics and polymers

Non-biodegradable materials such as plastics and other synthetic polymers are the most abundant and persistent environmental pollutants produced by humans. The accumulation of plastic waste is not only unsightly but presents a serious danger to living organisms, especially birds and marine animals. Entanglement and ingestion of non-biodegradable materials reduce the mobility and interfere with the digestive functions of affected species, which often leads to starvation and death. In a recent study over 95% of sea birds were found to have plastic objects in their stomachs, which in some cases prevented the birds from flying due to additional weight and chronic malnutrition.

While many traditional plastics are biologically inert and can remain in the environment for hundreds of years virtually unchanged, **biodegradable plastics** can be digested by microorganisms within a relatively short time. These materials either are composed of renewable biological materials such as starch (sub-topic B.4) and cellulose (sub-topic B.10), or contain additives that alter the structure of traditional plastics and allow microorganisms to digest hydrocarbon-based polymers. In addition, certain non-biodegradable plastics such as aromatic polyesters can be replaced with aliphatic polyesters (sub-topic A.9) that are very similar in structure and properties, but are less resilient to enzymatic hydrolysis. Another important component of biodegradable plastics, *polylactic acid* (*PLA*), is a condensation polymer of 2-hydroxypropanoic (lactic) acid:



2-hydroxypropanoic (lactic) acid — polylactic acid (PLA)

Starch-based polymers constitute over 50% of biodegradable plastics. By combining starch with natural plasticizers such as glycerol (sub-topic B.3) and certain carbohydrates, the characteristics of the resulting material can be varied significantly without compromising its biodegradability. Starch plastics are used for making a broad range of products from disposable bags and food packaging to mobile phones and car interiors. In some cases starch is blended with other polymers to create materials with desirable properties and reduce the use of fossil fuels as a hydrocarbon source.

Green chemistry

In traditional chemistry, the efficiency of a synthetic procedure is measured in terms of the product yield and the cost of raw materials while many other factors such as the toxicity of reagents and solvents, energy consumption, and the amount of waste produced are often ignored. A completely different approach, known as **green chemistry**, takes into account the environmental impact of the entire technological process and encourages the synthetic design that minimizes the use and generation of hazardous chemicals. Common practices of green chemistry include aqueous or solvent-free reactions, renewable starting materials, mild reaction conditions, regio- and stereoselective catalysis (sub-topics 20.1 and B.10), and the utilization of any by-products formed during the synthesis.

The term "green chemistry" was coined in 1991 by Paul Anastas and John Warner, who formulated 12 principles of their approach to chemical technology. These principles emphasize the benefits of non-hazardous chemicals and solvents, efficient use of energy and reactants, reduction of waste ("the best form of waste disposal is not to create it in the first place"), choice of renewable materials, and prevention of accidents. The philosophy of green chemistry has been adopted by many educational and commercial organizations and eventually passed into national and international laws, which restricted the use of certain chemical substances and encouraged the use of environmentally friendly technologies.

Atom economy

Another key concept of green chemistry, **atom economy**, expresses the efficiency of a synthetic procedure as the ratio of the mass of the isolated target product to the combined masses of all starting materials, catalysts, and solvents used in the reaction. For example, the atom efficiency of a solvent-free reaction $A + B \rightarrow C$ is equal to the practical reaction yield (sub-topic 1.3) and can potentially reach almost 100%. However, in a reaction $A + B \rightarrow C + D$ with the target product C, the atom efficiency will always be significantly lower than 100% because some of the atoms from reactants A and B form the unwanted by-product D. Solvents and catalysts further reduce the atom efficiency because their constituent atoms do not form the target product and must be disposed of or recycled.

The costs of green chemistry

Green technologies vary in efficiency and in many cases involve expensive equipment, raw materials, and recycling facilities. However, these initial investments reduce the costs associated with environmental remediation, waste management, and energy consumption, so in the long run green chemistry is a commercially attractive and sustainable alternative to traditional organic chemistry.

Increasing adoption of green industrial processes in developed countries has significantly reduced the emissions of many hazardous chemicals such as chlorinated solvents or greenhouse gases, and brought new products to the market. Many of these products including PLA and starch-based plastics are not only biodegradable but also can be produced by "green" technologies, which further decreases their overall environmental impact. At the same time, some non-hazardous substances branded as "green" or "environmentally friendly" still require toxic chemicals or large amounts of energy for their production. In addition, the industrial use of natural products such as plant oils and starch takes up agricultural resources and leads to various ecological and social issues (sub-topic B.4). Therefore the criteria used in assessing the "greenness" of a substance must include all direct and indirect environmental implications of its entire life cycle, which remains one of the most controversial problems in green chemistry.

Examples of atom-efficient reactions are the hydrogenation of alkenes (sub-topic 10.1) and unsaturated fats (sub-topic B.10), which proceed with high yields, require no solvents, and form almost no by-products under appropriate conditions. At the same time many traditional organic reactions such as the oxidation of alcohols (sub-topic 10.2) or electrophilic substitution in aromatic compounds (sub-topic 20.1) are very inefficient because they often require large volumes of solvents, have low yields, and, in some cases, produce mixtures of regio- and stereoisomers instead of individual target products.

Worked example

The alkylation of phenylamine can be carried out using traditional or green chemistry.

a) Dimethyl sulfate, $(CH_3O)_2SO_2$, is a traditional alkylating reagent that has many disadvantages including high toxicity and the possibility of side reactions. Calculate the percentage atom economy of the following reaction if the target product is *N*-methylphenylamine, $C_6H_5NHCH_3$:

$$2C_6H_5NH_2 + (CH_3O)_2SO_2 + 2NaOH \rightarrow 2C_6H_5NHCH_3 + Na_2SO_4 + 2H_2O$$

b) Dimethyl carbonate is a non-toxic and highly efficient alternative to dimethyl sulfate. Calculate the percentage atom economy of the following reaction:

$$C_6H_5NH_2 + (CH_3O)_2CO \rightarrow C_6H_5NHCH_3 + CH_3OH + CO_2$$

c) Dimethyl carbonate can be synthesized as follows:

$$4CH_3OH + 2CO + O_2 \rightarrow 2(CH_3O)_2CO + 2H_2O$$

Suggest how the amounts of waste produced in the synthesis of *N*-methylphenylamine can be further reduced.

Solution

a) The total mass of the products is equal to the total mass of the reactants, so it is sufficient to calculate the molecular masses of the products only: $M_r(C_6H_5NHCH_3) = 107.15$, $M_r(Na_2SO_4) = 142.04$, $M_r(H_2O) = 18.02$. The atom economy is $(2 \times 107.15)/(2 \times 107.15 + 142.04 + 2 \times 18.02) \approx 0.546$ or 54.6%.

b) $M_r(C_6H_5NHCH_3) = 107.15$, $M_r(CH_3OH) = 32.04$, $M_r(CO_2) = 44.01$. The atom economy is $107.15/(107.15 + 32.04 + 44.01) \approx 0.585$ or 58.5%.

c) Methanol formed in reaction (b) can be recycled and converted into dimethyl carbonate using reaction (c). In addition, carbon dioxide from reaction (b) can be recycled by the reaction with elemental carbon at high temperature: $CO_2 + C \rightarrow 2CO$. If both waste products are converted back into reactants, the atom economy of the entire technological process can reach almost 100%.