POLYLACTIC ACID

THE GREEN PLASTIC

VCE- Chemistry
Unit 4
Area of study 1
Outcome 1

Assessment task - Analysis and evaluation of a chemical innovation.

You have been provided with the stimulus materials below and they can be used during the assessment task under test conditions. This material provides the context of the questions asked. It is important to answer all questions using your knowledge of the Chemistry that has been covered related to the dot points of Unit 4 outcome 1.

This is a practice/revision task.

Key knowledge
Dot points to be covered in this revision task

Structure, nomenclature and properties of organic compounds

- characteristics of the carbon atom that contribute to the diversity of organic compounds formed, with reference to valence electron number, relative bond strength, relative stability of carbon bonds with other elements, degree of unsaturation (carbon-carbon double bonds), and the formation of structural isomers
- molecular, structural and semi-structural (condensed) formulas and skeletal structures of alkanes (including cyclohexane), alkenes, benzene, haloalkanes, primary amines, primary amides, alcohols (primary, secondary and tertiary), aldehydes, ketones, carboxylic acids and non-branched esters
- the International Union of Pure and Applied Chemistry (IUPAC) systematic naming of organic compounds up to C8, with no more than two functional groups for a molecule, limited to non-cyclic hydrocarbons, haloalkanes, primary amines, alcohols (primary, secondary and tertiary), aldehydes, ketones, carboxylic acids and non-branched esters
- trends in physical properties within and between homologous series (boiling point and melting point, viscosity), with reference to structure and bonding

Reactions of organic compounds

- organic reactions and pathways, including equations, reactants, products, reaction conditions and catalysts (specific enzymes not required):
  - synthesis of primary haloalkanes and primary alcohols by substitution
  - addition reactions of alkenes
  - the esterification between an alcohol and a carboxylic acid
  - hydrolysis of esters
  - pathways for the synthesis of primary amines and carboxylic acids
  - transesterification of plant triglycerides using alcohols to produce biodiesel
  - hydrolytic reactions of proteins, carbohydrates and fats and oils to break down large biomolecules in food to produce smaller molecules
  - condensation reactions to synthesise large biologically important molecules for storage as proteins, starch, glycogen and lipids (fats and oils)
  - enzymes as protein-based catalysts in living systems: primary, secondary, tertiary and quaternary structures and changes in enzyme function in terms of structure and bonding as a result of increased temperature (denaturation), decreased temperature (lowered activity), or changes in pH (formation of zwitterions and denaturation)
- calculations of percentage yield and atom economy of single-step or overall reaction pathways, and the advantages for society and for industry of developing chemical processes with a high atom economy
- the sustainability of the production of chemicals, with reference to the green chemistry principles of use of renewable feedstocks, catalysis and designing safer chemicals

In recent years, the growing concern over environmental sustainability has driven significant interest in the development and adoption of green plastics. Among these, polylactic acid (PLA) has emerged as a promising alternative to traditional petroleum-based plastics. PLA is a biodegradable thermoplastic derived from renewable resources such as corn starch, sugarcane, and other biomass. Its production and use offer a myriad of environmental benefits, including reduced carbon footprint and decreased dependency on fossil fuels.

Polylactic acid stands out not only for its eco-friendly origins but also for its versatility and applicability across various industries. It can be used in packaging, agriculture, biomedical devices such as sutures and 3D printing.

The adoption of PLA as a green plastic is supported by its favourable properties, such as high mechanical strength, clarity, and ability for composting. These characteristics make PLA particularly attractive for applications where both performance and environmental impact are critical considerations. As the global demand for sustainable materials continues to rise, PLA represents a significant step forward in the transition towards a more sustainable and circular economy.

While PLA can be considered an eco-friendly biomaterial with excellent properties, it also has many obvious drawbacks when confronted with requirements for certain applications:

1) Its degradation rate through hydrolysis of the backbone ester groups is slow and can sometimes take several years, which can limit its biomedical and food packaging applications.

2) PLA is very brittle and thus not suitable for demanding mechanical performance applications unless it is suitably modified.

3) PLA is permeable to gases and its wider industrial application is limited which prevents its complete access to industrial sectors such as packaging.

4) PLA is expensive relative to non-degradable plastics manufactured with feedstock from the petrochemical industry.

Figure 1 – Some uses of PLA aside from biomedical uses.

1. **Fermentation Dominance**: Over 90% of lactic acid production globally is achieved through the fermentation of carbohydrates derived from renewable resources like corn starch, sugarcane, and other biomass. This method is favoured for its sustainability, lower environmental impact and alignment with the circular economy principles.

   The biological fermentation route uses carbohydrates as substrates to produce lactic acid (LA) through microbial fermentation. Highly pure LA can be produced by a broad range of microorganisms, such as bacteria, fungi, algae and cyanobacteria. Furthermore, many low-cost biomass wastes, such as kitchen waste, straw and sludge contain a large number of degradable substances which can be used as substrates for the production of LA by biological fermentation. Currently, more than 90 % of LA in the world is produced by biological fermentation.

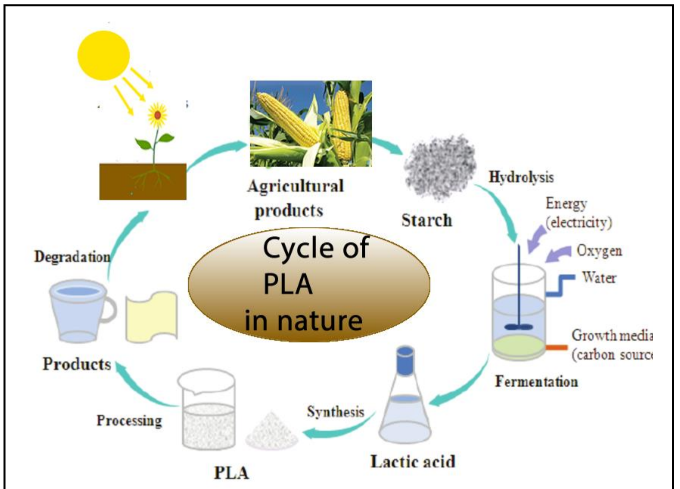

Figure 2 – PLA cycle via fermentation

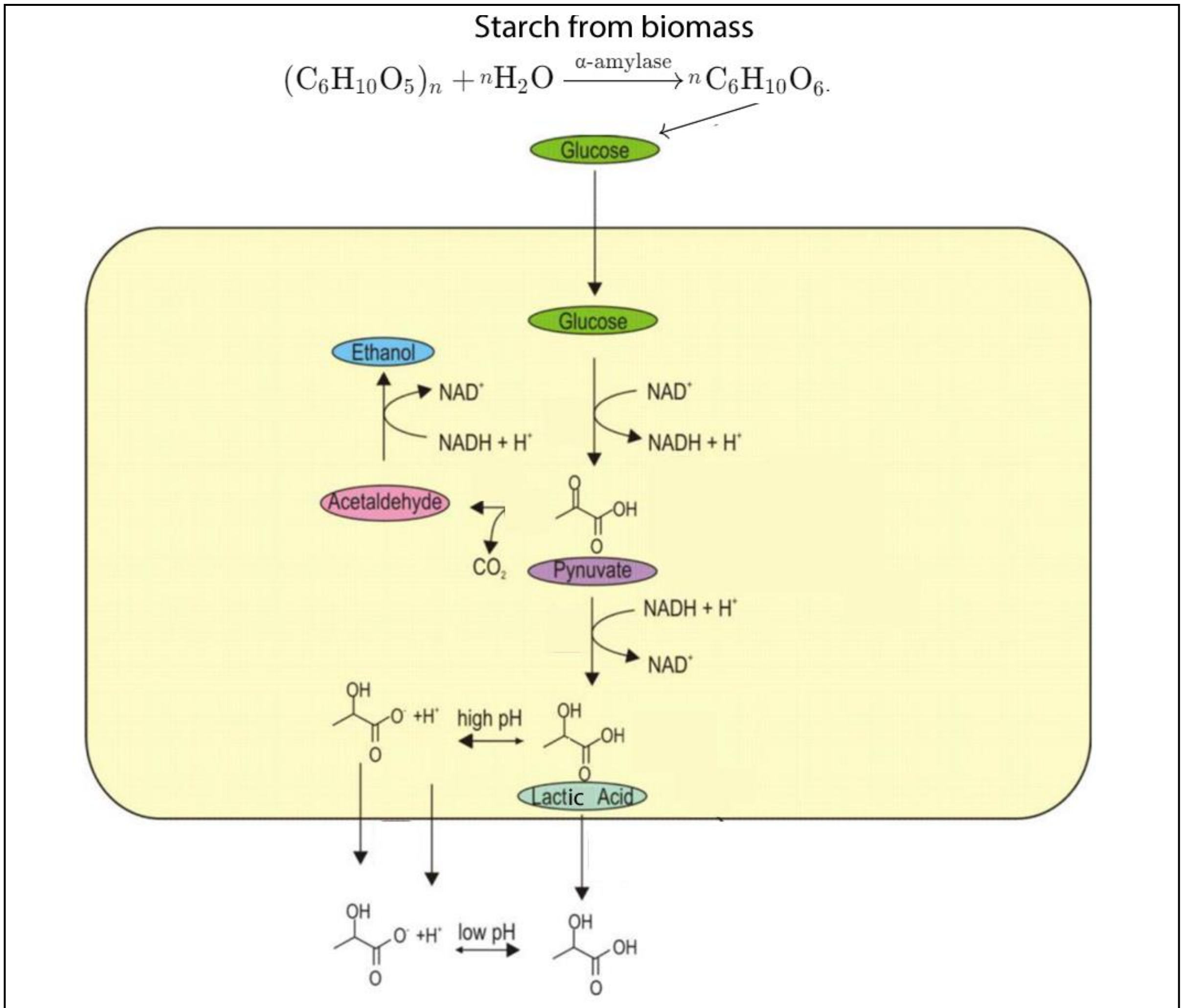

Figure 3 - fermentation pathway for the synthesis of lactic acid.

1. **Petrochemical Production**: The remaining 10%, comes from petrochemical sources. This method involves chemical synthesis from petrochemical derivatives such as acetaldehyde, which is converted to lactic acid through various chemical processes (fig 4). However, this method is less common due to concerns about the environmental impact and sustainability of using fossil fuels.

   The pathway to the chemical production of polylactic acid (PLA) is shown below in fig 4. Ethene, from the petrochemical industry, provides the feedstock for the process. This accounts for only 10% of the lactic acid used in industry to produce reusable and biodegradable plastics.

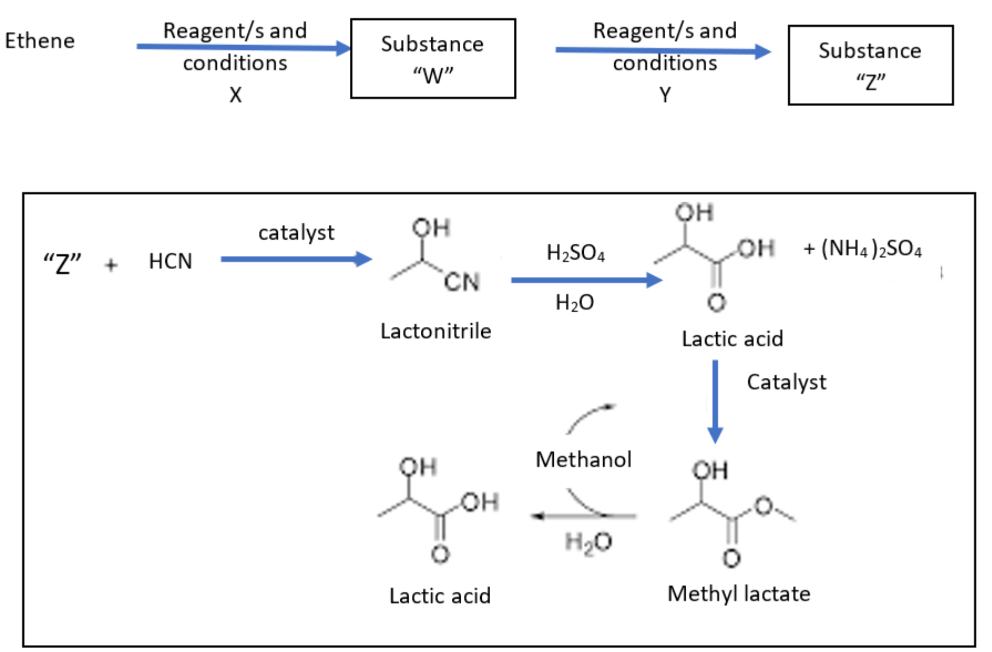

Figure 4 – Pathway for the chemical synthesis of lactic acid.

Fractional distillation, under reduced pressure, is used to separate lactic acid from impurities such as residual hydrogen cyanide and lactonitrile, both extremely toxic and to harmful to aquatic life. The BP of lactic acid is around 216 °C, however, at this high temperature the molecule starts to decompose thus reducing the overall yield. Under reduced pressure (vacuum), the boiling points of lactic acid is significantly lowered. For example, lactic acid boils at about 122°C at 15 mmHg, much lower than it would under atmospheric pressure. Fractional distillation is ultimately used to concentrate and purify the lactic acid.

1. Consider the reaction shown in fig 5.

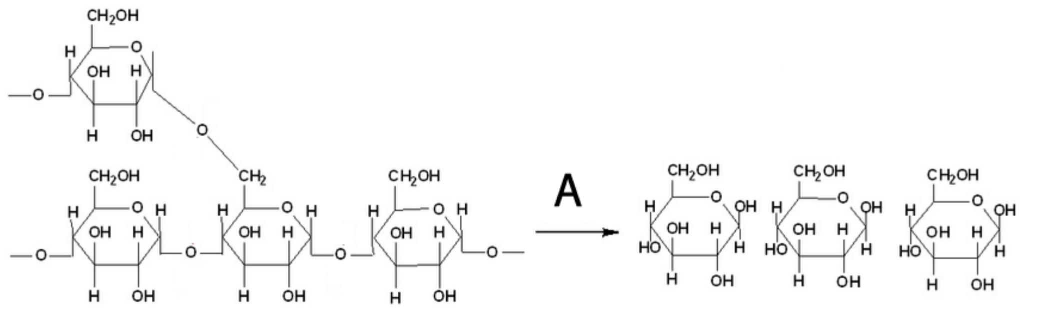

Figure 5 – enzymatic digestion of starch.

a. Name the reactant molecule.

____ ***1 mark***

b. Name the type of reaction that formed the reactant molecule.

____ ***1 mark***

c. Name the product molecule.

____ ***1 mark***

d. Name the type of reaction.

____ ***1 mark***

e. "A" represents a biological catalyst known as **α-amylase.** Alpha amylase works to cleave molecules from the ends of the molecular chains. A particular biomass (X) contains starch composed of 80% amylose and 20% amylopectin whilst another type of biomass (Y) contains starch composed of 70% amylopectin and 30% amylose.

   i. Biomass X and Y were exposed to **α-amylase** under exactly the same temperature and pH. Which biomass will yield product at the fastest rate? Explain

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____ ***2 marks***

ii. A student suggested that increasing the temperature of the reaction vessel to 55 ^{o}C, in which reaction A takes place, will cause a greater rate of product formation to occur as the average kinetic energy of all reactant particles is increased.

Is the student right? ___________ ***1 mark***

Give a detailed explanation, with reference to bonding and structure, to justify your response.

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____ ***3 marks***

2. Synthesis of lactic acid from biomass is preferred over synthesis of lactic acid via ethene. Identify and explain three green chemistry principles that support this preference, detailing how each principle is applied.

Principle 1 ____ ***1 mark***
Explanation____
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____ ***2 marks***

Principle 2 ____ ***1 mark***
Explanation____
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____ ***2 marks***

Principle 3 ____ ***1 mark***
Explanation____
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____ ***2 marks***

3. Consider the chemical pathway shown in fig 4 above.

a. Give the IUPAC name for lactic acid. ____ ***1 mark***

b. Identify the following: reagent:

Reagent Y ____ ***1 mark***
Reagent X ____ ***1 mark***
Substance W ____ ***1 mark***
Substance Z ____ ***1 mark***

c. A student was asked to identify the type of reaction that converts lactonitrile to lactic acid? Their response was that the reaction is a *"hydration reaction"*

i. Is the student correct? ____ ***1 mark***

ii. Justify your response to i. above.

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____***2 marks***

d. Consider the reaction pathway shown below.

i. In the box provided give the names of T, S and W. ***3 marks***

lactic acid + [T __________] —[S]→ methyl lactate + [W __________]

ii. Give the specific name for this type of reaction. ______________________________ ***1 mark***

e. Consider the information shown in table 1.

i. With reference to specific functional groups and intermolecular bonding, explain why methyl lactate has a lower boiling temperature than lactic acid even though it is a bigger molecule.

Substance	BP at 1 atm (°C)
Lactic acid	217
Methyl lactate	145

Table 1- boiling temperatures of lactic acid and methyl lactate at 1 atm.

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____***3 marks***

f. When purifying lactic acid from the reaction mixture distillation is used. Using your knowledge of chemistry and the information given to you in the extract above. Suggest a reason why the formation of methyl lactate is necessary.

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____***2 marks***

g. In the box below:

i. draw a small, two monomer, section of the polylactic acid. ***2 marks***

ii. In the box above, circle and clearly label a functional group present in your diagram of the small section of polylactic acid ***2 marks***

iii. Calculate the atom economy for the reaction of five lactic acid (formula mass = 90.09 amu) monomers to form a small section of PLA. Give your answer to the right number of significant figures. ***3 marks***

4. Does the use of PLA as a plastic material made from ethene derived from the petrochemical industry, represent a circular or linear economy? Define the terms "linear economy" and "circular economy," and explain your reasoning.

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____***4 marks***

5. Which two sustainable development goals are addressed by the use of fermentation to produce lactic acid for the synthesis of PLA? Justify your selection of each goal.

Goal 1 ____ ***1 mark***

Justification____
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____***1 mark***

Goal 2 ____ ***1 mark***

Justification____
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____***1 mark***