Please check the examination details below before entering your candidate information

Candidate surname	Other names

Centre Number | Candidate Number

Pearson Edexcel International Advanced Level

Tuesday 13 January 2026

Morning (Time: 1 hour 45 minutes)

Paper reference **WBI15/01**

Biology

International Advanced Level
UNIT 5: Respiration, Internal Environment, Coordination and Gene Technology

You must have:
Scientific article (enclosed), scientific calculator, ruler, HB pencil

Total Marks

Instructions

- Use **black** ink or ball-point pen.
- **Fill in the boxes** at the top of this page with your name, centre number and candidate number.
- Answer **all** questions.
- Answer the questions in the spaces provided – *there may be more space than you need*.

Information

- The total mark for this paper is 90.
- The marks for **each** question are shown in brackets – *use this as a guide as to how much time to spend on each question*.
- In the question labelled with an **asterisk (*)**, marks will be awarded for your ability to structure your answer logically, showing how the points that you make are related or follow on from each other where appropriate.

Advice

- Read each question carefully before you start to answer it.
- Try to answer every question.
- Check your answers if you have time at the end.

Turn over

Pearson

Answer ALL questions.

Write your answers in the spaces provided.

Some questions must be answered with a cross in a box ☒. If you change your mind about an answer, put a line through the box ☒ and then mark your new answer with a cross ☒.

1 Some drugs affect the transmission of nerve impulses.

(a) Nicotine and cobra venom alpha toxin (CV) are two drugs that affect the transmission of nerve impulses.

The table gives two statements about the action of these drugs.

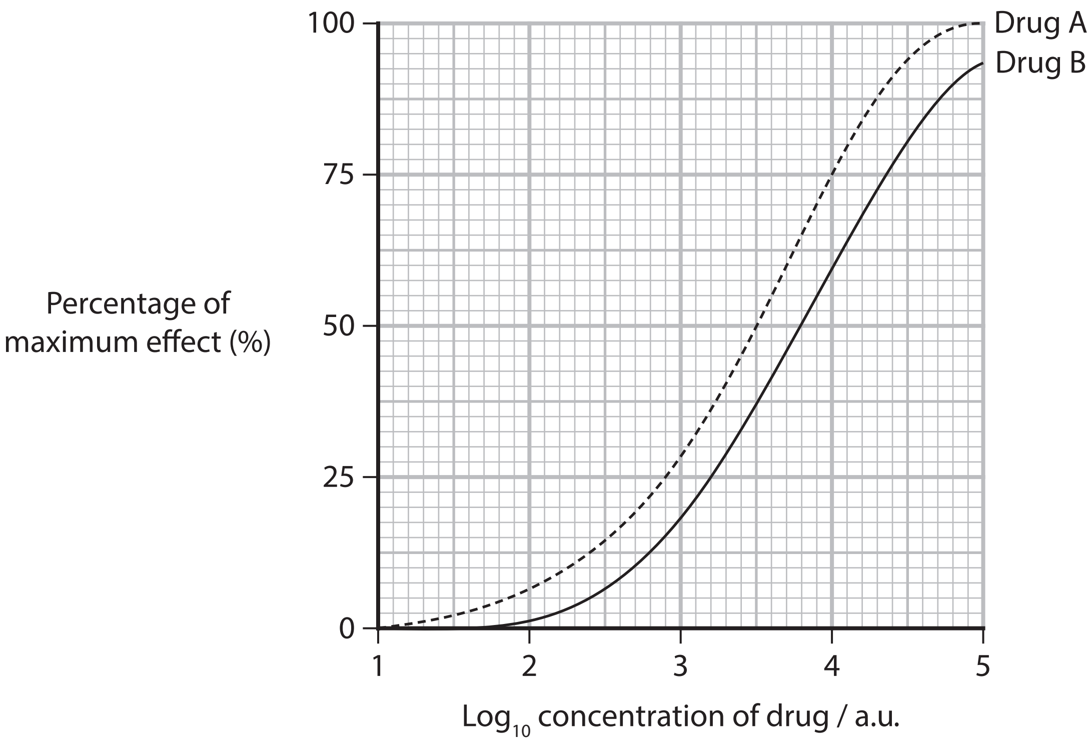
For each statement, put **one** cross ☒ in the appropriate box, in each row, to show whether these statements are true for nicotine and for CV.

(2)

Statement about the action of these drugs	**Type of drug**			
	both nicotine and CV	nicotine only	CV only	neither nicotine nor CV
Binds to acetylcholine receptor	☒	☒	☒	☒
Stimulates nerve impulses	☒	☒	☒	☒

(b) The effectiveness of a drug depends on the concentration used.

The graph shows the effect of the concentration used on the percentage of the drug's maximum effect, for two different drugs.



(i) Suggest why a $\log_{10}$ scale has been used on the x-axis.

(2)

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(ii) The concentration of a drug that causes 50% maximum effect is called the ED50.

Calculate the difference in the ED50 of these two drugs.

(2)

Answer .... a.u.

(Total for Question 1 = 6 marks)

2 The respiratory quotient (RQ) can indicate the respiratory substrate being used by an organism.

(a) (i) State how the RQ can be calculated.

(2)

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(ii) Explain why the RQ can be calculated only if oxygen is available to the organism.

Use your knowledge of the Krebs cycle to support your answer.

(2)

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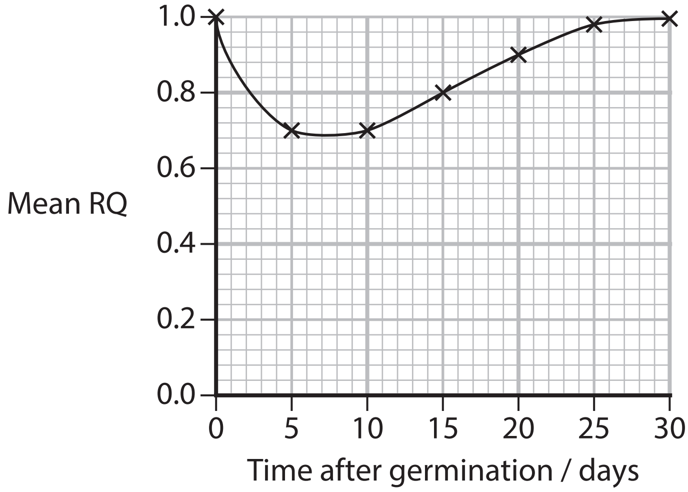
(b) The table shows the RQ for respiratory substrates containing different proportions of carbohydrate and lipid.

Proportion of carbohydrate	Proportion of lipid	RQ
1.0	0.0	1.00
0.8	0.2	0.88
0.6	0.4	0.80
0.4	0.6	0.76
0.2	0.8	0.73
0.0	1.0	0.70

(i) Determine the relationships between the proportions of carbohydrate and lipid and the RQ values.

(2)

(ii) The graph shows the mean RQ of barley grains at germination and for 30 days after germination.



Describe the conclusions that can be made about the respiratory substrates used by these barley grains.

Use the information in the table and this graph to support your answer.

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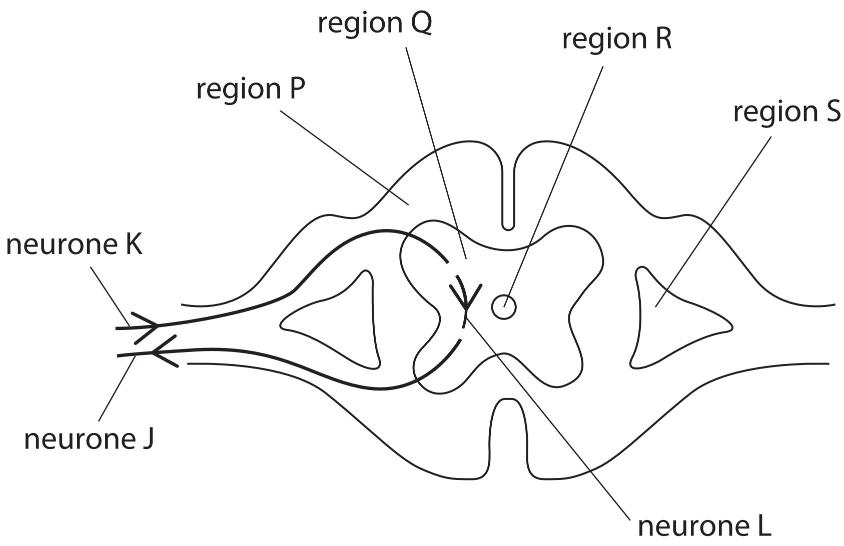
(Total for Question 2 = 9 marks)

3 (a) The diagram shows part of a spinal reflex arc.



(i) Which row of the table identifies neurones J, K and L?

(1)

		Neurone J	Neurone K	Neurone L
☒	**A**	motor	relay	sensory
☒	**B**	motor	sensory	relay
☒	**C**	relay	sensory	motor
☒	**D**	sensory	motor	relay

(ii) Draw one circle (●) on each of the three neurones in the diagram to show the position of their cell bodies.

(2)

(iii) Which region in the diagram is the grey matter?

(1)

☒ **A** region P

☒ **B** region Q

☒ **C** region R

☒ **D** region S

(b) When a nerve impulse arrives at the presynaptic membrane, a neurotransmitter is released into the synapse.

(i) Which ion channels open in this membrane when a nerve impulse arrives?

(1)

☒ **A** calcium ion channels

☒ **B** chloride ion channels

☒ **C** sodium ion channels

☒ **D** potassium ion channels

(ii) Which pair are neurotransmitters?

(1)

☒ **A** acetylcholine and guanine

☒ **B** adrenaline and acetylcholine

☒ **C** galactose and adrenaline

☒ **D** guanine and galactose

(c) When the neurotransmitter binds to the post-synaptic membrane, depolarisation of the membrane occurs.

Explain why this depolarisation is an example of positive feedback.

(4)

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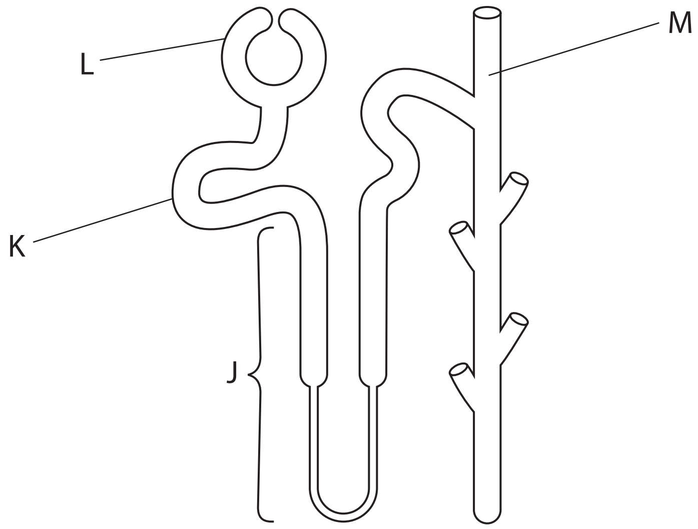
(Total for Question 3 = 10 marks)

4 The kidneys are involved in the filtration and reabsorption of glucose.

(a) The diagram shows a mammalian nephron.



(i) The length of the part of the nephron labelled J is 7 mm.

Calculate the magnification of this diagram.

Give your answer to **two** significant figures.

(1)

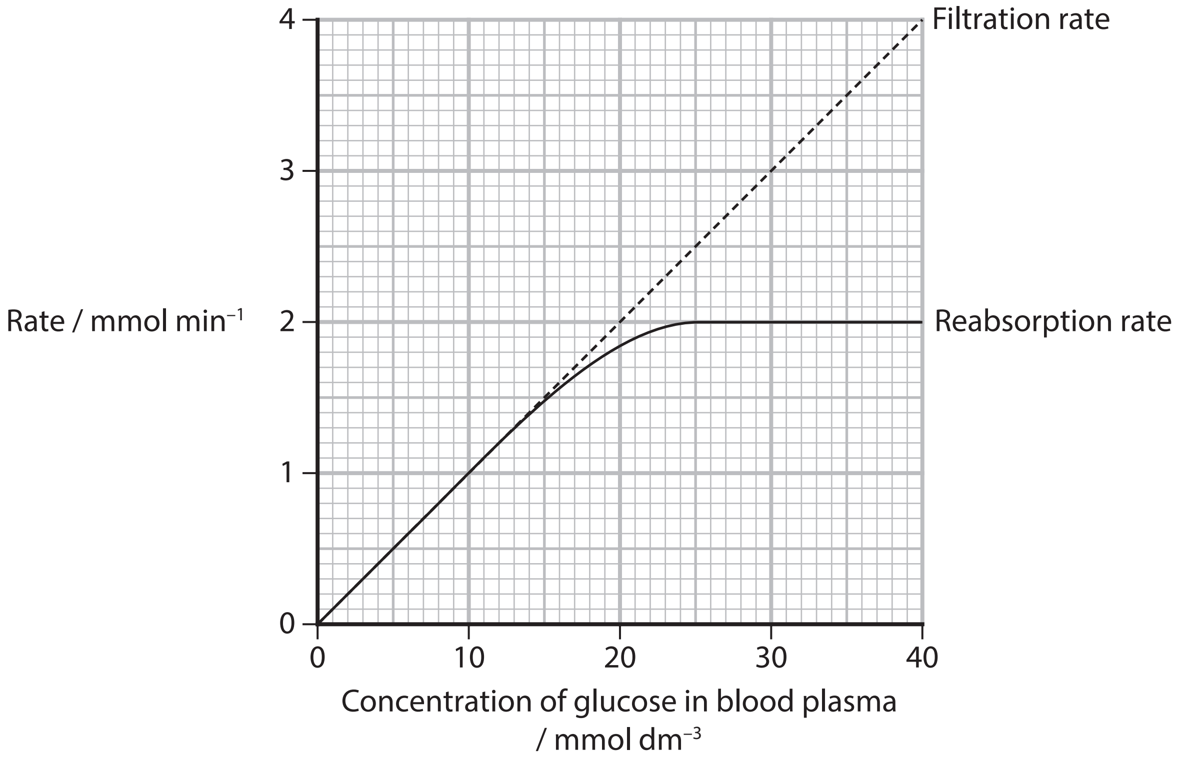
Answer ....

(ii) Which row of the table shows where the filtration and reabsorption of glucose occurs?

(1)

		Filtration of glucose	Reabsorption of glucose
☒	**A**	K	J
☒	**B**	K	L
☒	**C**	L	K
☒	**D**	L	M

(b) The graph shows how the rates of filtration and reabsorption of glucose in mammalian nephrons vary with the concentration of glucose in the blood plasma.



(i) Calculate the percentage increase in the rate of filtration when the concentration of glucose in the blood plasma increases from 5 mmol dm^{-3} to 35 mmol dm^{-3}.

(1)

Answer .... %

(ii) Describe how the filtration rate and the reabsorption rate change as the concentration of glucose in the blood plasma increases.

Use the values from the graph to support your answer.

(3)

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(iii) Give a reason why glucose is present in the urine when the concentration of glucose in the blood plasma rises above 12 mmol dm^{-3}.

(1)

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(Total for Question 4 = 7 marks)

5 Animals can learn to adjust their behaviour according to the environment they are in.

One example of this behaviour is habituation.

(a) (i) State the meaning of the term **habituation**.

(1)

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(ii) The photograph shows two elk crossing a road in the Grand Canyon.

(Source: ©Susan Vineyard/Alamy Stock Photo)

The elk have become habituated to the presence of humans and wander onto the roads to approach their cars.

Suggest **two** reasons why the habituation of these elk could be dangerous.

(1)

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(b) The effect of a food reward on the behaviour of rats was investigated in a laboratory.

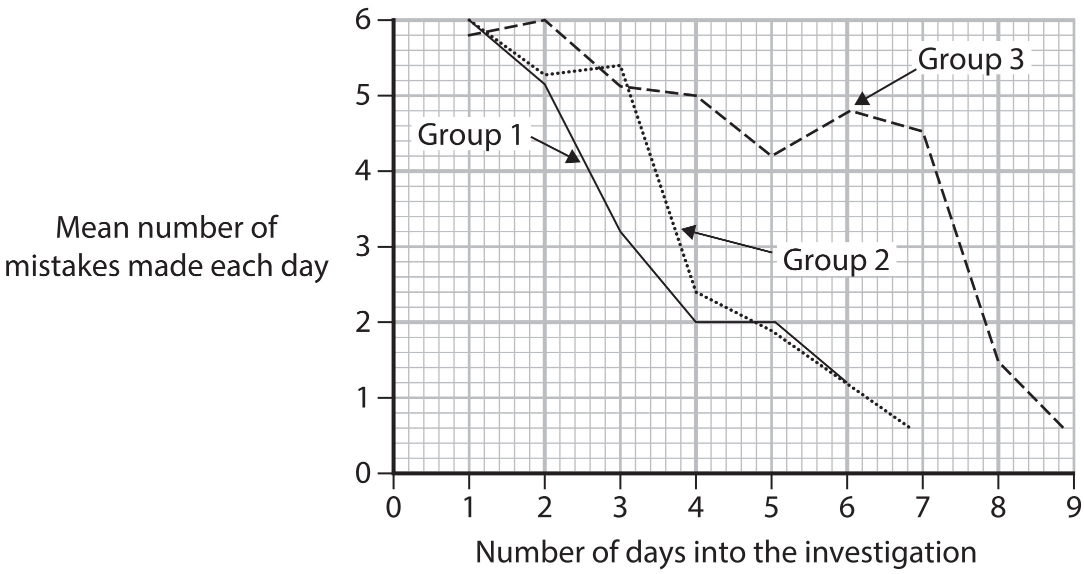
Three groups of rats were placed in a maze every day for nine days.

The number of mistakes that the rats made in finding their way from the start of the maze to the end of the maze was recorded.

The table shows how the investigation was set up for each group of rats.

Group of rats	Investigation set-up
1	A food reward placed at the end of the maze each day of the investigation
2	A food reward placed at the end of the maze from day 3 onwards
3	A food reward placed at the end of the maze from day 6 onwards

The graph shows the results of this investigation.



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P 7 9 0 3 5 A 0 1 4 3 2

(i) Calculate the ratio of the mean number of mistakes made on day 4 by these three groups.

Give your answer in the form Group 1 : Group 2 : Group 3.

(2)

Answer ....

(ii) Explain the results for the group 1 and group 3 rats.

(3)

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(Total for Question 5 = 7 marks)

6 Exercise affects cardiac output and the distribution of blood around the body.

(a) Cardiac output (CO) can be calculated using heart rate (HR) and stroke volume (SV).

Which equation shows how cardiac output can be calculated?

(1)

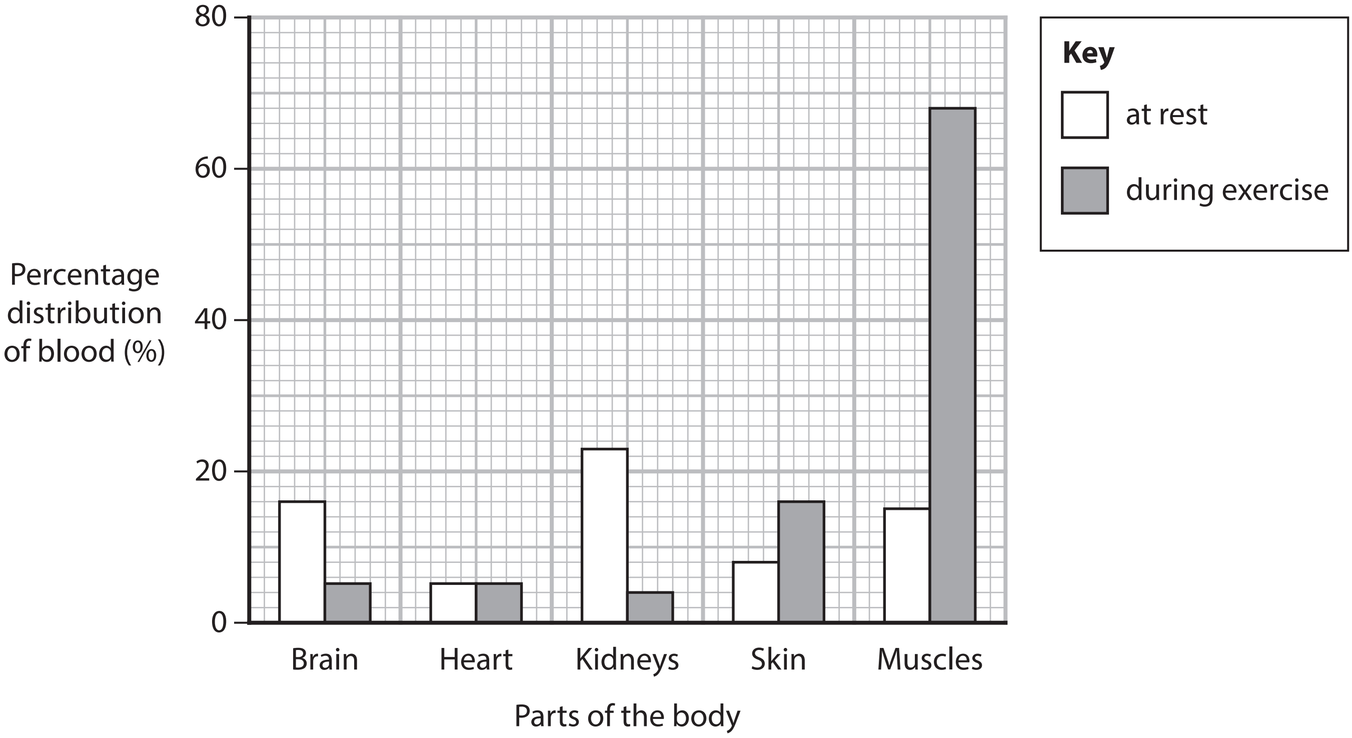
☒ **A** CO = HR ÷ SV

☒ **B** CO = SV ÷ HR

☒ **C** CO = SV × HR

☒ **D** CO = SV – HR

(b) The graph shows the percentage distribution of blood in some parts of the body of a person at rest and during exercise.



(i) The total volume of blood in this person is 5 dm^3.

Calculate the volume of blood in the muscles of this person during exercise.

(1)

Answer .... dm^3

(ii) Explain the effect of exercise on the change in percentage distribution of blood in the kidneys and skin.

(4)

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(c) These electrocardiograms (ECGs) are from a person at rest and during exercise.

At rest

During exercise

Describe **two** conclusions that can be made about the effect of exercise on the **cardiac cycle** in this person.

(2)

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(Total for Question 6 = 8 marks)

P 7 9 0 3 5 A 0 1 8 3 2

7 Molecules that absorb light are present in animals and plants.

(a) Describe how absorption of light by molecules in rod cells results in hyperpolarisation of these cells.

(3)

*(b) Phytochromes are involved in the germination of lettuce seeds.

Phytochromes exist in two interconvertible forms, P_R and P_{FR}.

In an investigation, groups of lettuce seeds were treated with different sequences of red light (R), far red light (FR) and periods of darkness.

The table shows the sequences of treatment that each group received and whether the lettuce seeds germinated or not.

<table>
<tr><th>Group</th><th colspan="3">Length of treatment</th><th>Seeds germinated</th></tr>
<tr><td>1</td><td colspan="3">red light</td><td>yes</td></tr>
<tr><td>2</td><td colspan="3">darkness</td><td>no</td></tr>
<tr><td>3</td><td>red light</td><td colspan="2">darkness</td><td>yes</td></tr>
<tr><td>4</td><td>red light</td><td>far red light</td><td>darkness</td><td>no</td></tr>
<tr><td>5</td><td>far red light</td><td>red light</td><td>darkness</td><td>yes</td></tr>
</table>

0 | 12 hours | 24 hours

Explain the role of phytochromes in the germination of lettuce seeds in this investigation.

Use the information in the table and your own knowledge to support your answer.

(6)

(Total for Question 7 = 9 marks)

8 Skeletal muscle consists of both fast and slow twitch muscle fibres.

(a) Which of the following statements are correct?

1. Slow twitch muscle fibres store **more** myoglobin than fast twitch muscle fibres.
2. Slow twitch muscle fibres have **fewer** mitochondria than fast twitch muscle fibres.
3. Slow twitch muscle fibres fatigue **faster** than fast twitch muscle fibres.

(1)

☒ **A** Statement 1 only

☒ **B** Statement 2 only

☒ **C** Statements 1 and 3 only

☒ **D** Statements 1, 2 and 3

(b) Some sports training programmes result in an increase in the network of capillaries around muscle fibres.

Explain the benefit to muscles of an increased network of capillaries.

(3)

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(c) A student used muscle fibres to investigate factors that affect muscle contraction.

The flow chart shows the procedure that was followed.

Strands of fresh muscle fibres were cut to the same length and separated out on three microscope slides, A, B and C

↓

Muscle fibres on each slide were covered in a different solution that had the same water potential as the cytoplasm of the muscle fibres:

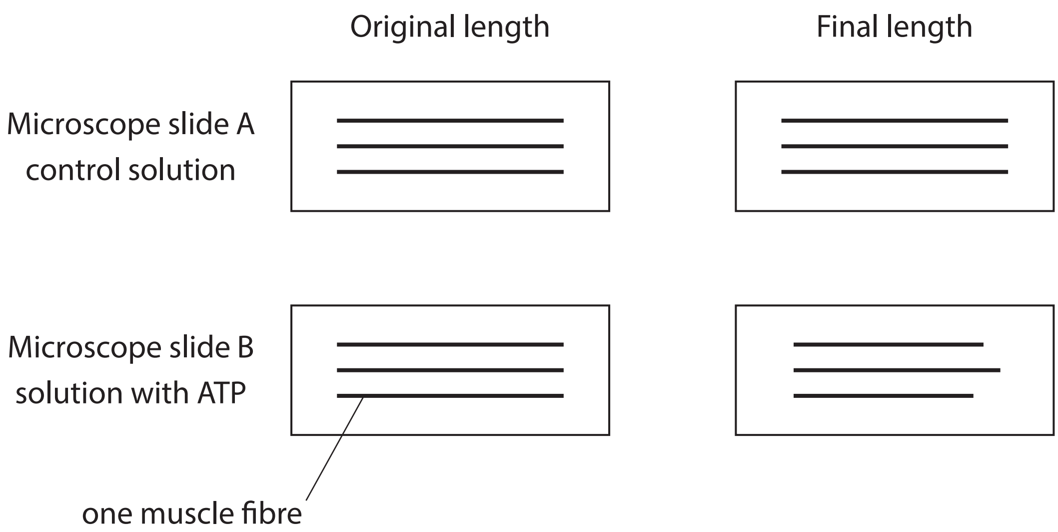
- Microscope slide A had a control solution added
- Microscope slide B had a solution with ATP added
- Microscope slide C had a solution with glucose added

↓

The muscle fibres were left in the solution for five minutes and the lengths of the fibres measured again

The diagram shows the results for slides A and B.

All the muscle fibres in the diagram are drawn to the same scale.



(i) Explain why the solutions had the same water potential as the cytoplasm of the muscle fibres.

(2)

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(ii) Suggest what the control solution contained.

(1)

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(iii) The original length of each fibre was 3 cm.

The final length of each fibre in the control solution was 3 cm.

Calculate the percentage decrease in the **mean** length of the fibres on microscope slide B.

(2)

Answer .... %

(iv) Explain why adding ATP to the muscle fibres on microscope slide B caused a decrease in length.

(3)

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(v) The muscle fibres on microscope slide C were shorter than 3 cm but not as short as those in the ATP solution.

Suggest why these fibres were shorter than 3 cm but not as short as those in the ATP solution.

(2)

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(Total for Question 8 = 14 marks)

9 The scientific document you have studied is adapted from an article in *Nature Communications*: 'The Microbial Food Revolution'.

Use the information from the scientific document and your own knowledge to answer the following questions.

(a) Explain **two** reasons why our current food system can be described as involving unsustainable practices (paragraph 1).

(2)

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(b) Explain why plant-based foods are less environmentally harmful than animal-based foods (paragraph 2).

(2)

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(c) Explain how alcoholic products (paragraph 5) are produced by microorganisms grown in anaerobic conditions.

(4)

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(d) Explain why probiotic supplements could help to maintain health (paragraph 8).

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(e) Explain the advantage of reducing free radicals in vegetable and fruit products (paragraph 11).

(2)

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(f) Explain why microorganisms often have high levels of RNA (paragraph 18).

(2)

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(g) Explain how microorganisms could be genetically modified to be more suitable for the human palate (paragraph 20).

(3)

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(h) Explain the purpose of the numbers in amongst the text, for example the numbers 1, 2 and 3 (paragraph 2).

(2)

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(Total for Question 9 = 20 marks)

TOTAL FOR PAPER = 90 MARKS

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Tuesday 13 January 2026

Morning (Time: 1 hour 45 minutes)

Paper reference **WBI15/01**

Biology

International Advanced Level

UNIT 5: Respiration, Internal Environment, Coordination and Gene Technology

Scientific document for use with Question 9

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P 7 9 0 3 5 A

Pearson

Scientific article for use with Question 9

The microbial food revolution

Abstract

1 Our current food system relies on unsustainable practices, which often fail to provide healthy diets to a growing population. Therefore, there is an urgent demand for new sustainable nutrition sources and processes. Microorganisms have gained attention as a new food source solution, due to their low carbon footprint, low reliance on land, water and seasonal variations coupled with a favourable nutritional profile. Furthermore, with the emergence and use of new tools, specifically in synthetic biology, the uses of microorganisms have expanded showing great potential to fulfil many of our dietary needs. In this review, we look at the different applications of microorganisms in food, and examine the history, state-of-the-art and potential to disrupt current foods systems. We cover both the use of microbes to produce whole foods out of their biomass and as cell factories to make highly functional and nutritional ingredients. The technical, economical, and societal limitations are also discussed together with the current and future perspectives.

Introduction

2 The current food systems have been pushed to a crisis, as they struggle to keep up with nutrition and protein demand coupled with population growth[1]. All our food systems—agriculture, animal husbandry and aquaculture—are grappling with the degradation of land, climate change and climate disasters, which are set to rise in the future[2]. Although moving towards plant-based foods is less environmentally harmful, it still relies on climate or season and intensive land, water and chemical use[3]. The time for a microbial revolution in food is ripe as microorganisms have the potential to enhance, improve or even replace the currently available alternatives[4,5]. They have been proven to be an ecological and resilient food source, especially when compared to traditional protein sources such as meat[6,7]. Genetic and system design can advance sustainability further when renewable and waste feedstocks are considered[8,9]. Furthermore, they are highly resilient due to their decentralised nature that does not rely on location limitations, such as temperature or weather[10]. Finally, they also have a high nutritional profile[11], crucial in the face of rising diet-related health epidemics.

3 Microorganisms are no stranger in the history of food; however, research has lately revealed the vast array of health benefits and ecological savings that can be derived from using microorganisms in food[12,13]. This has led to an explosion in new applications, improvement in traditional practices using state-of-the-art technology[14,15,16] and a better understanding of their roles and benefits[13]. Fermentation can be used both directly on foods to improve nutrition, taste or texture[17,18], as well as used as a production platform to produce value-added ingredients in the food industry[19,20,21]. Moreover, using fermentation to produce microbial biomass as a nutritional food source is starting to be adopted in both animal feed and human foods[22,23,24]. However, there are challenges to overcome in each of these applications, including scalability and economic or ecological sustainability. Novel tools can be applied to these fields to enhance and accelerate the development of microbial-based foods and overcome current limitations. This includes high-resolution and high-throughput characterisation of microorganisms[14,25], as well as genetic and metabolic engineering tools[4]. By engineering and selecting strains, it is possible to improve flavour[26] and nutrition[20,27,28] as well as increase sustainability using waste feed or cheap non-competing carbon sources[8,29]. This can

contribute to increasing applications and uptake to propel a microbial revolution in food.

4 Due to the high potential and varied applications of microbes in food, there have been numerous recent start-ups in this space, ranging from improving traditional fermentation to creating new products. Development is still needed for technical advances and consumer acceptance but the field of single-cell proteins and engineered microbes in food has high potential, as will be explored in this review. This review aims to give an overview of the different applications of microorganisms in food ranging from traditional fermentation techniques to biotech applications of ingredient production. It covers the different novel applications of microbes in the food system as well as the role of synthetic biology in advancing this field. Finally, the obstacles and future perspectives will be considered.

The use of microbes in food

Rise of fermentation in history

5 Microorganisms were first leveraged by humans in the food system for fermentation. Fermentation is one of the earliest known food technologies dating as far back as 7000BC or earlier and arising independently in multiple ancient cultures[30,31]. Alongside smoking and salting, fermentation was a primary method of food preservation and thus a crucial technology in the rise of human civilisations[32]. In addition, the process also introduced many new products, flavours and tastes. Different fermented products rose from specific environments and conditions which produced a diversity of edible products[32]. These include, but are not limited to, dairy products such as cheese and yoghurt, alcoholic products such as beer and wine, fermented bean products such as soy sauce, douche and natto, other vegetables such as sauerkraut and kimchi and many more[32].

6 The advent of new processing and preservation methods such as refrigeration, the use of natural and artificial preservatives, and freezing and vacuum sealing, among others, have provided alternatives to traditional fermentation. However, more recently, research has brought to our attention the many health benefits offered by a microbial presence in food[13,33], causing a resurgence in popularity, and many newly popularised health foods are fermented or have fermented ingredients. This is compounded by the rise of plant-based diets and increasing access to international foods—many of which include traditionally fermented products. A good example is Kombucha, a traditional Manchurian fermented tea drink which was introduced to the international market with many purported health benefits and now is valued at over 1 billion US dollars[34]. Other well-known examples are Tempeh and Tofu, two fermented soybean products from Indonesia and China, respectively, which are now consumed as meat-alternative protein sources globally[35].

Different functions and health benefits of fermented foods

7 Fermentation, in the context of food, refers to raw material undergoing enzymatic conversions in the presence of microorganisms[13,36]. These conversions result in alteration in their physicochemical properties. Many of the resulting metabolites play an active role in food preservation, inhibiting the growth of contaminating or spoiling pathogens and increasing shelf life, but others contribute to nutrition, texture, taste and smell[13]. Depending on their composition, fermented food may also bring health benefits. The list is a brief summary of some of the most relevant benefits, although comprehensive reviews can be found on the topic[18,37]:

8 Microbiome enhancing (or probiotic) qualities: The gut microbiome is increasingly proving to be crucial for maintaining health[38]. The use of probiotics supplements has become widely adopted, although the health benefit and strain formulation remain controversial topics[39]. The consumption of certain fermented foods themselves has proven to have probiotic and health-promoting effects[40].

9 Increasing bioavailability of nutrients in food: This is due to microorganisms breaking food down for easier digestion and absorption of ingested nutrients. For example, lactic acid fermentation can increase the food's iron content by optimising pH and acid content for solubility[41]. Similarly, fermentation can improve the nutritional value of food by interfering with anti-nutritional factors, which impede protein, carbohydrate or phytochemical availability. For example, trypsin inhibitors found abundantly in various cereals, grains and legumes have been shown reduced activities in fermented foods[42].

10 Reducing Glycaemic Index: The Glycaemic Index (GI) measures how quickly carbohydrates in food raise blood glucose levels[43]. Probiotic and/or fermented cereals, pseudo-cereals and dairy products have been linked to a reduction in the GI of the food and the blood sugar response[43,44]. Lowering GI intake and response has been shown to reduce risk factors for diseases such as type II diabetes and cardiovascular disease[43].

11 Removing toxins: Microbial consortia can also act by removing toxic compounds and inhibiting the growth of pathogenic species. For example, Aflatoxin, a common toxin found in foods contaminated with *Aspergillus flavus*, has been shown to be enzymatically reduced in various fermentative processes[45]. Free radicals in vegetable and fruit products are also reduced during fermentation[46].

12 Biochemical pathways producing health-promoting compounds: Many microorganisms naturally produce nutritionally beneficial chemical compounds including but not limited to antioxidants, polyunsaturated fatty acids, conjugated linoleic acids (CLA), sphingolipids, vitamins and minerals[4,47,48].

13 However, fermentation does not always improve the foods and undesired microorganisms can negatively impact some nutritional aspects. Some examples include the production of toxic biogenic amines by lactic acid bacteria[35], including an increase of free histamine due to the high presence of histidine-producing enzymes (L-histidine decarboxylase) in microorganisms[49]. To counteract this, strategies have been developed to either optimise strain selection[50] or use engineered strains to enhance biogenic amine degradation[51]. Finally, it is also worth noting that many health claims related to fermented foods are yet to be fully verified by randomised controlled trial studies and have often been exaggerated for marketing purposes[52].

The nutritional profile of microbes

14 Microbial biomass itself also often has qualities that lend itself to consumption as food, including high protein, fibre and bioactive compound content.

15 All microorganisms are generally characterised by high protein content, with algal species averaging between 40–60%, fungi 30–70% and bacteria averaging between 53 to as high as 80%[11,12]. Furthermore, many species are complete amino acid sources, containing adequate amounts of essential amino acids which humans cannot synthesise and need to acquire from diet[53]. In addition, many microbes have a high content of essential amino acids that are lacking in plants[54].

16 Fibres, resistant carbohydrates that are key in maintaining gut health[55], are also elevated in many microbial species[11]. Algae, for instance, has a high fibre content that is composed mainly of insoluble fibres, cellulose and other polysaccharides found in their cell walls[56]. Both filamentous fungi and yeast have potentially beneficial fibres, namely β-glucan and mannan-oligosaccharides, both of which are consumed as health supplements for gut health and immune-boosting effects[57,58].

17 Although lipid content is generally low compared to animal products, oleaginous yeasts and algae are a source of high-value dietary lipids, especially long-chain polyunsaturated fatty acids[34,59]. Interestingly, the overall calorie content can be quite low, such as in commercially available nutritional yeast flakes, which contain 400 calories per 100 g, bringing a high ratio of nutrition to energy. Finally, microorganisms often have high endogenous contents of nutritionally relevant compounds, including vitamins, minerals, antioxidants and other functional ingredients[11].

18 The nutritional profile of microorganisms requires further investigation as their use becomes more widespread. The true digestibility of the elements discussed above has not been fully elucidated[11] and the compositions can differ widely based on different species and the environments in which they are grown[60]. Species need to be carefully selected as some microorganisms also have significant safety and health detriments. An elevated RNA content is often seen in microorganisms which can lead to health issues, such as gout and kidney stones[61]. Some fungal and bacterial species also produce allergens and toxins and are thus ill-suited as food or require processing before ingestion[11]. By carefully choosing species, substrates, and conditions, the nutritional aspects of the food can be modulated to suit specific needs.

Obstacles and future perspectives

Technical obstacles

19 To have a fully incorporated use of microbes in food, there are some technical difficulties that must be overcome. First, one of the main nutritional drawbacks is the high content of nucleic acids—namely RNA content. Ingestion of excessive quantities of nucleic acids particularly purines, increases the quantity of uric acid in the body which is a risk factor for gout and renal calculi as well as a strong risk factor for Metabolic Syndrome and cardiovascular disease[112]. This can be partially mitigated through processing methods, including heating and purification as employed by current single-cell protein manufacturers[113,114]. In the future, it would be possible to envisage an inducible method engineered into microbes to self-purify excess nucleic acids.

20 As a sole food source, the odours and textures of pure microbial cell mass have been postulated to be unsuited to human palate, however this setback could be improved through breeding or engineering in taste with genetic modifications or by creating mixtures or co-cultures to have novel and pleasant tastes[16,115].

21 Many microorganisms, especially yeast, fungal and algal clades also have thick cell walls. In many cases, this is an important contributor of fibre in the diet. However, for some SCP, the thick cell wall can limit the number of nutrients that can be taken up and can itself be indigestible. Therefore, it may be necessary to treat the SCP using heat and/or mechanical and enzymatic processes, improving nutrient bioavailability[114].

Food safety

22 Microbial-based foods and ingredients must go through regulatory approvals, which are stricter when new or engineered species are used. Regulatory bodies assess safety and authorize foods in a country-specific manner. For example, the FDA and EFSA are the main regulatory bodies in the USA and Europe, respectively. Some strategies to facilitate the obtention of approvals for microbial foods include the use of approved organisms and processes, limiting the application to animal feeding, purification of products, and removing foreign DNA and living cells.

23 The safety of the foods must also be considered for each different species. There has already been extensive investigation into some of the main target species that have confirmed their food safety both for fermentation, ingredient production and SCP use. Special attention must be paid to possible contamination in the process and to the potential production of endo and exotoxins that cause allergic and adverse reactions when ingested. Some toxins may be removed by simple heat or chemical treatments. However, through stringent strain selection[116], strain engineering[117] and correct fermentation technologies, contamination and toxin production can be prevented or eliminated.

Conclusion

24 Taken together all the information discussed above, there is an obvious interest in developing more microbial-based foods and ingredients, as seen by the increased number of related academic publications, conferences, companies and commercial products. This is in part encouraged by the consumer demand for healthier and more sustainable foods.

25 Synthetic biology and microbial strain engineering broaden the horizons of microbial foods that can be designed, enabling the creation of desired nutritional profiles, aroma compounds, flavours and textures, all of which can build towards personalised nutrition. To translate this technological capability into sustainable commercial products, the public perception of microbial foods must continue to change and the legislation must facilitate the implementation of these novel processes while maintaining high safety standards. The expansion and normalisation of microbial foods will increase production volumes, decreasing costs and optimising the efficiency of the technology. Reduced costs can then aid the development of microbial processes in less developed areas of the planet, which often need to improve nutrition. Looking at the future, engineered microbes are expected to play a role in delivering food where traditionally inaccessible, such as in disaster relief, deserts or even in space[124,125].

26 In conclusion, if there is continued innovation and microbial foods are designed with sustainability and ethics in mind, they have the potential to revolutionise current food systems. This microbial food revolution could be key in designing future-proof strategies to face the health and environmental challenges of the future.

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