La-Net

BIO 203

GENERAL PHYSIOLOGY

Course code: BIO 203

Course title: General Physiology

Course credit load: 2 Units

Series 1: Chemistry of Organic Compounds

- ## Part 1.1: Carbohydrates
  - Sub Part 1.1.1: Structure and classification of carbohydrates
  - Sub Part 1.1.2: Properties of carbohydrates
  - Sub Part 1.1.3: Biological importance of carbohydrates
- ## Part 1.2: Lipids
  - Sub Part 1.2.1: Structure and classification of lipids
  - Sub Part 1.2.2: Properties of lipids
  - Sub Part 1.2.3: Biological importance of lipids
- ## Part 1.3: Proteins
  - Sub Part 1.3.1: Amino acids and protein structure
  - Sub Part 1.3.2: Properties of proteins
  - Sub Part 1.3.3: Biological importance of proteins
- ## Part 1.4: Nucleic Acids
  - Sub Part 1.4.1: Structure of DNA and RNA
  - Sub Part 1.4.2: Properties of nucleic acids
  - Sub Part 1.4.3: Biological importance of nucleic acids

Introduction

Living organisms are built from and powered by a relatively small set of organic molecules: carbohydrates, lipids, proteins, and nucleic acids. These four classes of biological macromolecules carry out all the structural, energetic, catalytic, regulatory, and informational functions that together constitute life at the molecular level. Understanding their chemistry is therefore the essential foundation of physiological understanding.

This opening Series examines the structure, classification, properties, and biological importance of each of the four major classes of organic compounds. This molecular-level knowledge underpins the enzyme biochemistry, nutritional physiology, membrane biology, and regulatory physiology examined in the remaining Series of this course.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 1.1** describe the structure, classification, properties, and biological importance of carbohydrates,
- **SLO 1.2** describe the structure, classification, properties, and biological importance of lipids,
- **SLO 1.3** describe the structure of amino acids and proteins, and explain the biological importance of proteins, and
- **SLO 1.4** describe the structure, properties, and biological importance of nucleic acids.

1.1 Carbohydrates

1.1.1 Structure and classification of carbohydrates

Carbohydrates are organic compounds composed of carbon, hydrogen, and oxygen, typically in a ratio approximating CH2O (hence the name carbohydrate, meaning hydrated carbon); they are classified by the number of monomer sugar units present: monosaccharides (single sugar units, such as glucose, fructose, and galactose) are the simplest and most fundamental carbohydrates; disaccharides (two monosaccharides joined by a glycosidic bond, such as sucrose, maltose, and lactose) form by condensation reactions; and polysaccharides (many monosaccharide units linked together, such as starch, glycogen, and cellulose) form large, structurally complex molecules.

Glucose ($C_6H_{12}O_6$) is the central monosaccharide in biology, existing in ring form in solution and serving as the primary fuel for cellular respiration in virtually all living organisms; the way glucose units are joined together in polysaccharides (the type of glycosidic bond and the degree of branching) determines the physical properties and biological role of the resulting polysaccharide, explaining why starch and cellulose, both built from glucose, have very different digestibility and structural properties.

Fill in the blank: Carbohydrates are classified into monosaccharides, disaccharides, and ________ based on the number of monomer sugar units present.

1.1.2 Properties of carbohydrates

Monosaccharides and disaccharides are generally soluble in water (hydrophilic) due to their numerous hydroxyl groups forming hydrogen bonds with water molecules, and many are sweet-tasting; they are reactive molecules, reducing sugars (such as glucose, fructose, and maltose) capable of acting as reducing agents due to a free aldehyde or ketone group, a property exploited in the Benedict and Fehling tests used to detect reducing sugars in biological samples.

Polysaccharides display quite different physical properties from simple sugars: they are generally insoluble or only sparingly soluble in water (particularly cellulose), tasteless, and not sweet; their physical properties (solubility, viscosity, and gelling behaviour) are determined by their monomer sequence, degree of polymerisation, and the type and degree of branching, making polysaccharides extremely versatile molecules with widely varying physical characters despite sharing a carbohydrate chemical identity.

Fill in the blank: ________ sugars, such as glucose and maltose, can act as reducing agents due to a free aldehyde or ketone group, a property detected by the Benedict test.

1.1.3 Biological importance of carbohydrates

Carbohydrates serve as the primary energy source in most living organisms: glucose is oxidised through cellular respiration to yield ATP (adenosine triphosphate), the universal cellular energy currency; starch (in plants) and glycogen (in animals and fungi) serve as energy storage polysaccharides that can be broken down to release glucose when energy demands rise; and the pentose sugars ribose and deoxyribose form essential structural components of RNA and DNA respectively.

Structural roles of carbohydrates include cellulose (a principal structural component of plant cell walls, providing rigidity and strength), chitin (a structural polysaccharide forming the exoskeleton of arthropods and the cell wall of fungi), and various glycoproteins and glycolipids on cell surfaces that play important roles in cell recognition, immune response, and cell-cell signalling.

Fill in the blank: ________ serves as the energy storage polysaccharide in animals and fungi, broken down to release glucose when energy demands rise.

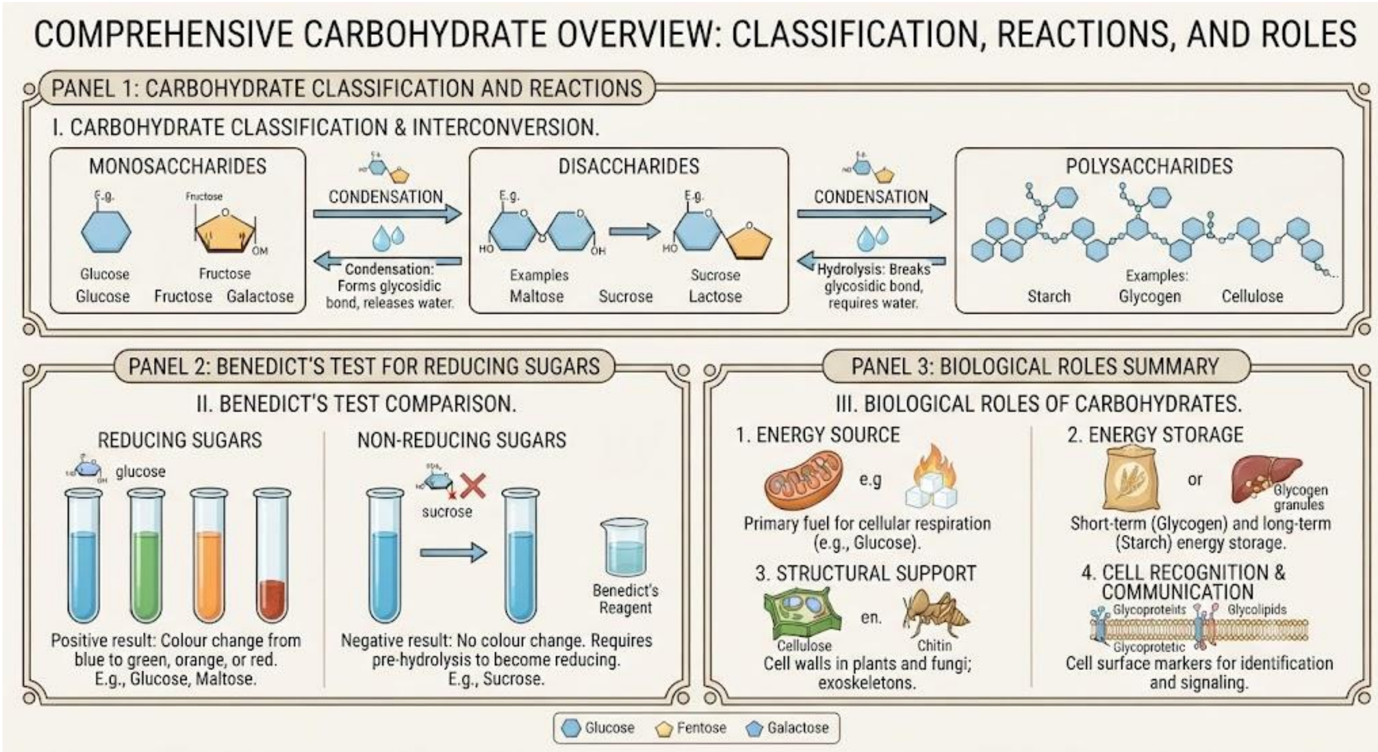

Figure 1.1: Carbohydrate structure and classification

Pilot questions 1.1

1. Name the three classes of carbohydrates and give one example of each.
2. Explain why starch and cellulose have different properties despite both being made of glucose.
3. Define a reducing sugar and name two examples.
4. Name two biological roles of polysaccharides.
5. State the biological importance of the pentose sugars ribose and deoxyribose.

1.2 Lipids

1.2.1 Structure and classification of lipids

Lipids are a diverse group of organic compounds defined not by a common chemical structure but by a shared physical property: they are insoluble in water but soluble in non-polar organic solvents such as ether, chloroform, and benzene; the major lipid classes are triglycerides (triacylglycerols, composed of one glycerol molecule esterified with three fatty acid chains, the main form of fat storage in animals and plants), phospholipids (similar to triglycerides but with one fatty acid replaced by a phosphate-containing group, essential components of cell membranes), and sterols (including cholesterol and steroid hormones, characterised by a distinctive four-ring carbon skeleton).

Fatty acids, the component chains of triglycerides and phospholipids, are classified as saturated (all carbon-carbon bonds in the chain are single bonds, generally solid at room temperature, such as palmitic and stearic acid found in animal fats) or unsaturated (containing one or more carbon-carbon double bonds, generally liquid at room temperature, such as oleic acid in olive oil and the polyunsaturated fatty acids found in many plant and fish oils).

Fill in the blank: Lipids are defined by their shared physical property of being insoluble in ________ but soluble in non-polar organic solvents.

1.2.2 Properties of lipids

The hydrophobic (water-repelling) nature of lipids arises from their predominantly non-polar hydrocarbon chains, which cannot form hydrogen bonds with water and are therefore excluded from aqueous environments; triglycerides are entirely hydrophobic, making them ideal energy-dense storage molecules, while phospholipids are amphipathic (having both a hydrophilic phosphate head and hydrophobic fatty acid tails), a dual character that drives the spontaneous formation of the lipid bilayer structure of cell membranes.

The degree of unsaturation (number and arrangement of double bonds) in fatty acid chains profoundly affects lipid physical properties: saturated fatty acids pack closely together, forming relatively solid, high-melting-point fats (such as butter and lard), while unsaturated fatty acids, with their kinked double-bond geometry, cannot pack as closely, producing lower-melting-point oils (such as vegetable and fish oils) that remain liquid at lower temperatures.

Fill in the blank: Phospholipids are ________ , having both a hydrophilic phosphate head and hydrophobic fatty acid tails, driving the formation of lipid bilayer membranes.

1.2.3 Biological importance of lipids

Lipids serve as the most energy-dense biological fuel, storing approximately twice the caloric energy per gram compared to carbohydrates or proteins, making triglyceride fat reserves the principal long-term energy store in most animals; the insulating properties of subcutaneous fat also provide thermal insulation and cushioning of internal organs; and phospholipids form the fundamental structural component of all biological membranes, governing which substances can cross the membrane.

Sterols have diverse and critical regulatory functions: cholesterol is an essential component of animal cell membranes (influencing membrane fluidity) and the precursor for the biosynthesis of steroid hormones (including sex hormones such as oestrogen and testosterone, and adrenal hormones such as cortisol); fat-soluble vitamins (A, D, E, and K) are lipid-derived or lipid-associated molecules with essential roles in vision, calcium metabolism, antioxidant defence, and blood clotting respectively.

Fill in the blank: ________ is an essential component of animal cell membranes and the precursor for steroid hormone biosynthesis.

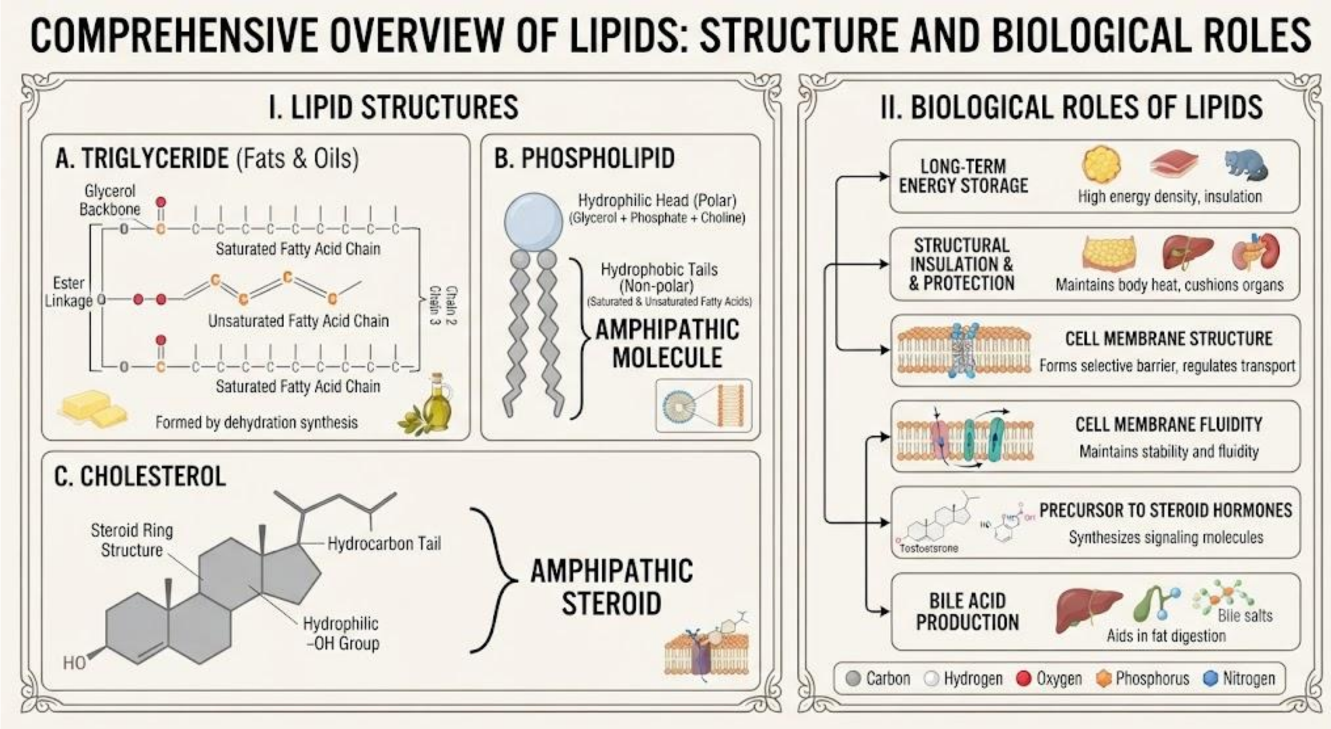

Figure 1.2: Lipid structure and biological roles

Pilot questions 1.2

1. Name the three major classes of lipids.
2. Distinguish between saturated and unsaturated fatty acids and explain how they differ in physical state at room temperature.
3. Define amphipathic and explain why phospholipids are amphipathic.
4. Explain why lipids are a more energy-dense fuel than carbohydrates.
5. Name two biological roles of cholesterol.

1.3 Proteins

1.3.1 Amino acids and protein structure

Proteins are polymers of amino acids, each amino acid consisting of a central carbon atom (alpha carbon) bonded to an amino group (-NH2), a carboxyl group (-COOH), a hydrogen atom, and a variable side chain (R group) that determines the chemical character and properties of that particular amino acid; twenty standard amino acids are used by living organisms to build proteins, differing only in their R groups, which range from simple non-polar hydrocarbons to polar, charged, or aromatic groups.

Protein structure is described at four levels: primary structure (the specific sequence of amino acids joined by peptide bonds, determined by the gene encoding the protein); secondary structure (local regular folding patterns stabilised by hydrogen bonds, primarily the alpha helix and the beta pleated sheet); tertiary structure (the overall three-dimensional folding of the polypeptide chain, stabilised by interactions among R groups including hydrogen bonds, ionic interactions, disulfide bridges, and hydrophobic interactions); and quaternary structure (the arrangement of two or more polypeptide chains, present only in multi-subunit proteins such as haemoglobin).

Fill in the blank: Protein ________ structure is the specific sequence of amino acids joined by peptide bonds, determined by the gene encoding that protein.

1.3.2 Properties of proteins

Proteins display highly variable physical and chemical properties that reflect both their amino acid composition and their three-dimensional conformation: some proteins are soluble and globular (such as enzymes and antibodies), while others are insoluble and fibrous (such as collagen and keratin); proteins are amphoteric, capable of acting as either acids or bases depending on pH, since both amino and carboxyl groups are present throughout the molecule.

Denaturation, the disruption of a protein three-dimensional structure without breaking the primary sequence peptide bonds, occurs in response to heat, extreme pH, or certain chemicals, typically causing loss of biological activity; denaturation illustrates the critical importance of the higher-order structure for protein function, since the primary amino acid sequence alone is insufficient for activity without the correct three-dimensional folding.

Fill in the blank: ________ is the disruption of a protein three-dimensional structure without breaking peptide bonds, caused by heat, extreme pH, or chemicals, typically causing loss of biological activity.

1.3.3 Biological importance of proteins

Proteins carry out a wider range of biological functions than any other class of macromolecule: enzymes (biological catalysts, examined in detail in the next Series) are proteins; structural proteins (collagen in connective tissue, keratin in hair, nails, and skin, actin and myosin in muscle) provide mechanical support and generate movement; transport proteins (haemoglobin transporting oxygen in blood, various membrane transport proteins) carry substances across membranes and through the body.

Regulatory proteins (hormones such as insulin, and regulatory transcription factors controlling gene expression), immune proteins (antibodies/immunoglobulins defending against pathogens), receptor proteins (detecting signals at the cell surface and initiating intracellular responses), and contractile proteins (enabling muscle contraction and cell movement) further illustrate the extraordinary functional diversity of proteins, arising from the combinatorial variety possible with twenty amino acid building blocks and the capacity of proteins to fold into highly specific three-dimensional shapes.

Fill in the blank: ________ are proteins that defend against pathogens, illustrating one of the many regulatory and defensive functions carried out by this macromolecule class.

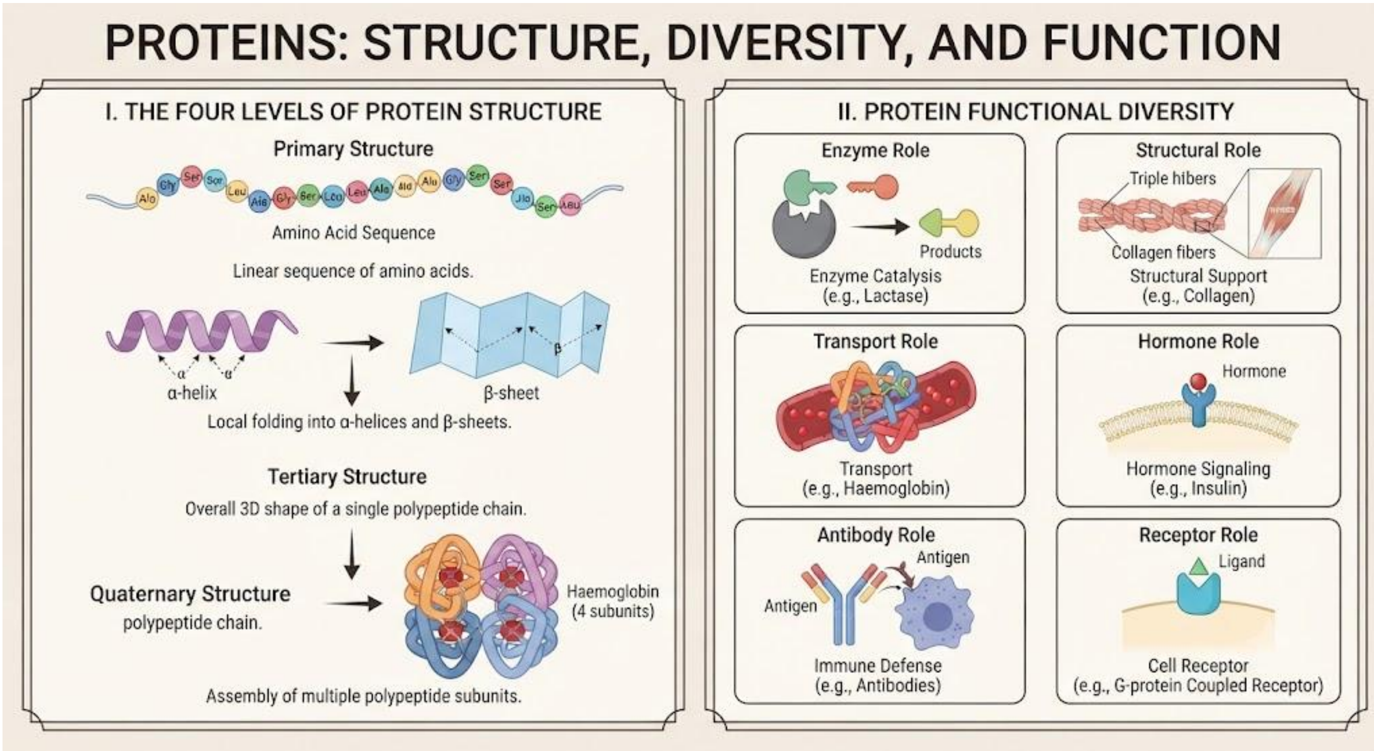

Figure 1.3: Protein structure and biological roles

Pilot questions 1.3

1. Name the four levels of protein structure and describe each briefly.
2. State what determines the primary structure of a protein.
3. Name two types of secondary structure in proteins.
4. Define denaturation and name two agents that can cause it.
5. Name four biological functions of proteins.

1.4 Nucleic Acids

1.4.1 Structure of DNA and RNA

Nucleic acids are polymers of nucleotides, each nucleotide consisting of three components: a pentose sugar (deoxyribose in DNA, ribose in RNA), a phosphate group, and a nitrogenous base; the nitrogenous bases in DNA are adenine, thymine, guanine, and cytosine, while RNA contains uracil instead of thymine; nucleotides are joined by phosphodiester bonds between the sugar of one nucleotide and the phosphate of the next, forming a sugar-phosphate backbone with the bases projecting to the side.

DNA is typically double-stranded, with two antiparallel polynucleotide chains held together by hydrogen bonds between complementary base pairs (adenine pairs with thymine via two hydrogen bonds; guanine pairs with cytosine via three hydrogen bonds), and the two strands wound around each other in a double helix; RNA is typically single-stranded and occurs in several functional forms including messenger RNA (mRNA, carrying genetic information from DNA to ribosomes), transfer RNA (tRNA, carrying amino acids during translation), and ribosomal RNA (rRNA, structural and catalytic component of ribosomes).

Fill in the blank: In DNA base pairing, adenine pairs with ________ and guanine pairs with cytosine, with the two strands wound in a double helix.

1.4.2 Properties of nucleic acids

DNA is a highly stable molecule adapted for long-term information storage: the double-stranded structure with complementary base pairing provides redundancy (allowing accurate repair if one strand is damaged using the other as a template) and the deoxyribose sugar is more chemically stable than ribose; DNA is located primarily in the nucleus of eukaryotic cells, with small amounts in mitochondria and chloroplasts.

RNA is generally less stable than DNA (the 2-OH group on ribose making it more susceptible to hydrolysis), reflecting its role as a transient messenger rather than a permanent information store; different RNA types have different stabilities, with structural rRNA being relatively stable while mRNA is often rapidly turned over to allow gene expression to be dynamically regulated in response to changing cellular needs.

Fill in the blank: DNA is more chemically stable than RNA because the ________ sugar lacks the 2-OH group that makes ribose susceptible to hydrolysis.

1.4.3 Biological importance of nucleic acids

DNA carries the hereditary genetic information of virtually all living organisms, encoding in its base sequence the instructions for building and operating the organism, from the sequence of every protein the organism can produce to the regulatory information controlling when and where each gene is expressed; the fidelity with which DNA is replicated and the mechanisms for repairing DNA damage are critical to maintaining the genetic integrity of organisms and species across generations.

RNA plays the central functional role in gene expression: mRNA carries the genetic information transcribed from DNA to the ribosome, where it is translated (with the help of tRNA and rRNA) into the amino acid sequence of a specific protein, realising the genetic information as a functional biological molecule; beyond this central coding role, various non-coding RNA molecules have regulatory roles in gene expression, chromosome structure, and other cellular processes, making RNA a functionally far more diverse molecule than its role as a simple messenger might suggest.

Fill in the blank: ________ RNA carries the genetic information from DNA to the ribosome, where it is translated into the amino acid sequence of a protein.

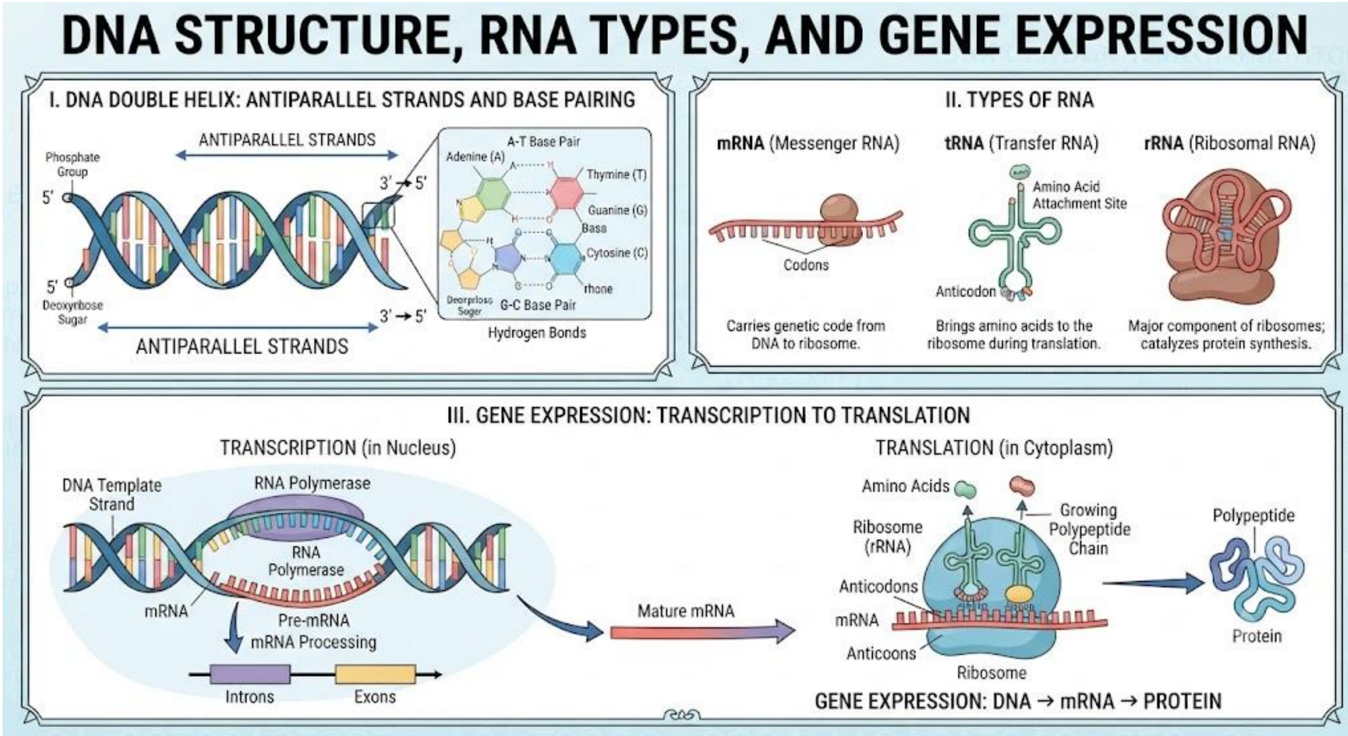

Figure 1.4: Nucleic acid structure and function

Pilot questions 1.4

1. Name the three components of a nucleotide.
2. Distinguish between the bases found in DNA and those found in RNA.
3. Explain the complementary base pairing rules in DNA.
4. Explain why DNA is more stable than RNA.
5. Describe the roles of mRNA, tRNA, and rRNA in protein synthesis.

Series Summary

This Series introduced the major **biological macromolecules** that form the structural and functional basis of living organisms. You explored the structure, composition, properties, and biological functions of carbohydrates, lipids, proteins, and nucleic acids, including their roles in energy storage, cell structure, metabolism, and the storage and expression of genetic information. The Series also highlighted important concepts such as reducing sugars, saturated and unsaturated fats, protein structure and denaturation, and the central dogma of molecular biology.

Building on these foundations, the Series explained how the structure of each biomolecule determines its function in living systems and how these molecules work together to support growth, metabolism, reproduction, and heredity. By completing this Series, you should now be able to identify and compare the major classes of biological macromolecules, relate their structures to their functions, distinguish between DNA and RNA, and explain the flow of genetic information from DNA to protein, thereby achieving all four **Series Learning Outcomes (SLOs 1.1 to 1.4)**.

Glossary of Terms

- **Amphipathic:** having both hydrophilic and hydrophobic regions, as in phospholipids.
- **Complementary base pairing:** the specific hydrogen-bonded pairing of adenine with thymine (DNA) and guanine with cytosine.
- **Denaturation:** disruption of protein or nucleic acid three-dimensional structure without breaking the primary covalent bonds.
- **Glycosidic bond:** the covalent bond joining two monosaccharide units in a disaccharide or polysaccharide.
- **Peptide bond:** the covalent bond joining the amino group of one amino acid to the carboxyl group of another.
- **Phosphodiester bond:** the covalent bond joining nucleotides in a nucleic acid polymer.
- **Reducing sugar:** a carbohydrate with a free aldehyde or ketone group capable of acting as a reducing agent.

Concept Check Questions [Series 1]

Objective Questions

1. Carbohydrates are classified into monosaccharides, disaccharides, and ________ . (Linked to SLO 1.1)
2. Phospholipids are ________ , having both a hydrophilic head and hydrophobic tails. (Linked to SLO 1.2)
3. Protein ________ structure is the specific amino acid sequence joined by peptide bonds. (Linked to SLO 1.3)
4. In DNA, adenine pairs with ________ and guanine pairs with cytosine. (Linked to SLO 1.4)
5. ________ RNA carries genetic information from DNA to the ribosome for translation. (Linked to SLO 1.4)

Short-Answer Questions

6. Name three biological roles of carbohydrates. (Linked to SLO 1.1)
7. Distinguish between saturated and unsaturated fatty acids. (Linked to SLO 1.2)
8. Name the four levels of protein structure. (Linked to SLO 1.3)
9. Name the three components of a nucleotide. (Linked to SLO 1.4)
10. Explain why DNA is more stable than RNA. (Linked to SLO 1.4)

Long-Answer Questions

11. Describe the structure, properties, and biological importance of carbohydrates and lipids. (Linked to SLOs 1.1, 1.2)
12. Describe the structure and biological importance of proteins. (Linked to SLO 1.3)
13. Describe the structure, properties, and biological importance of nucleic acids. (Linked to SLO 1.4)

Answers to Concept Check Questions [Series 1]

Objective Questions

1. Polysaccharides.
2. Amphipathic.
3. Primary.
4. Thymine.
5. Messenger (mRNA).

Short-Answer Questions

6. Energy source (glucose), energy storage (starch/glycogen), and structural roles (cellulose/chitin).
7. Saturated fatty acids have only single C-C bonds and are solid at room temperature; unsaturated have one or more double bonds and are liquid.
8. Primary, secondary, tertiary, and quaternary.
9. A pentose sugar, a phosphate group, and a nitrogenous base.
10. Deoxyribose in DNA lacks the 2-OH group that makes ribose in RNA susceptible to hydrolysis.

Long-Answer Questions

11. Carbohydrates (C, H, O) are classified as mono-, di-, or polysaccharides; monosaccharides are water-soluble reducing sugars; polysaccharides are insoluble storage or structural molecules. Lipids are water-insoluble, classified as triglycerides (energy storage), phospholipids (membrane structure), and sterols (membrane fluidity, hormone precursors).

12. Proteins are amino acid polymers with four structural levels (primary-quaternary); denaturation destroys function without breaking peptide bonds. Functions include enzymes, structural support, transport, hormones, antibodies, and receptors.
13. Nucleic acids are nucleotide polymers. DNA is double-stranded with deoxyribose and A-T/G-C base pairing, stable hereditary information storage. RNA is single-stranded with ribose; mRNA carries information, tRNA brings amino acids, rRNA forms ribosomes.

Answers to Pilot Questions [Series 1]

Part 1.1

1. Monosaccharides (glucose), disaccharides (sucrose), and polysaccharides (starch).
2. The type of glycosidic bond and branching differs; starch has alpha bonds (digestible) while cellulose has beta bonds (indigestible to most animals).
3. A reducing sugar has a free aldehyde or ketone group; examples: glucose and maltose.
4. Energy storage (starch, glycogen) and structural roles (cellulose, chitin).
5. Ribose is a structural component of RNA; deoxyribose is a structural component of DNA.

Part 1.2

1. Triglycerides, phospholipids, and sterols.
2. Saturated fatty acids have only single C-C bonds and are solid at room temperature; unsaturated have one or more double bonds and are liquid.
3. Amphipathic means having both hydrophilic and hydrophobic regions; phospholipids have a hydrophilic phosphate head and hydrophobic fatty acid tails.
4. Lipids store approximately twice the energy per gram compared to carbohydrates.
5. Cholesterol is an essential membrane component influencing fluidity, and a precursor for steroid hormone biosynthesis.

Part 1.3

1. Primary: amino acid sequence; secondary: local folding (helix, sheet); tertiary: overall 3D fold; quaternary: multi-subunit assembly.
2. The gene encoding the protein determines its primary structure.

3. Alpha helix and beta pleated sheet.
4. Denaturation is disruption of 3D structure without breaking peptide bonds; agents include heat and extreme pH.
5. Enzymes, structural proteins, transport proteins, and hormones (or antibodies, receptors).

Part 1.4

1. A pentose sugar, a phosphate group, and a nitrogenous base.
2. DNA has adenine, thymine, guanine, and cytosine; RNA has uracil instead of thymine.
3. Adenine pairs with thymine (2 hydrogen bonds); guanine pairs with cytosine (3 hydrogen bonds).
4. DNA has deoxyribose lacking the 2-OH group present in RNA ribose, making DNA more resistant to hydrolysis.
5. mRNA carries genetic information from DNA to the ribosome; tRNA brings amino acids during translation; rRNA is a structural and catalytic component of the ribosome.

References and Attributions

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Figure 1.1: Carbohydrate structure and classification Attribution: AI generated. Suggested OER search string: "carbohydrate classification monosaccharide disaccharide polysaccharide glycosidic bond biology OER".
- Figure 1.2: Lipid structure and biological roles Attribution: AI generated. Suggested OER search string: "lipid structure triglyceride phospholipid cholesterol fatty acid saturated unsaturated biology OER".
- Figure 1.3: Protein structure and biological roles Attribution: AI generated. Suggested OER search string: "protein structure primary secondary tertiary quaternary amino acid peptide bond biology OER".
- Figure 1.4: Nucleic acid structure and function Attribution: AI generated. Suggested OER search string: "DNA double helix RNA structure gene expression transcription translation biology OER".

Course code: BIO 203

Course title: General Physiology

Course credit load: 2 Units

Series 2: Enzymes and Their Characteristics

- **Part 2.1: Nature and General Properties of Enzymes**
  - Sub Part 2.1.1: Definition and nature of enzymes
  - Sub Part 2.1.2: General characteristics of enzymes
  - Sub Part 2.1.3: Enzyme nomenclature and classification
- **Part 2.2: Enzyme Structure and the Active Site**
  - Sub Part 2.2.1: Enzyme structure
  - Sub Part 2.2.2: The active site and enzyme-substrate interaction
  - Sub Part 2.2.3: Cofactors and coenzymes
- **Part 2.3: Factors Affecting Enzyme Activity**
  - Sub Part 2.3.1: Effect of temperature
  - Sub Part 2.3.2: Effect of pH
  - Sub Part 2.3.3: Effect of substrate concentration and enzyme concentration
- **Part 2.4: Enzyme Inhibition and Regulation**
  - Sub Part 2.4.1: Competitive inhibition
  - Sub Part 2.4.2: Non-competitive inhibition
  - Sub Part 2.4.3: Allosteric regulation and feedback inhibition

Introduction

Enzymes are the biological catalysts that make life possible at physiological temperatures: without them, the chemical reactions essential for cellular metabolism would proceed far too slowly to sustain life. Every metabolic pathway, from glucose breakdown to protein synthesis to DNA replication, depends on a precisely coordinated set of enzymes, each accelerating a specific reaction with remarkable selectivity.

This Series covers the nature, general properties, and classification of enzymes; enzyme structure and the mechanism of substrate binding at the active site; the major factors that influence enzyme activity, including temperature, pH, and substrate concentration; and the mechanisms of enzyme inhibition and allosteric regulation. This enzyme knowledge underpins the nutritional physiology, membrane transport, and broader metabolic topics addressed in the remaining course content.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 2.1** describe the nature, general properties, and classification of enzymes,
- **SLO 2.2** explain enzyme structure, the active site, and the roles of cofactors and coenzymes,
- **SLO 2.3** explain the effects of temperature, pH, and substrate concentration on enzyme activity, and
- **SLO 2.4** distinguish competitive from non-competitive inhibition and explain allosteric regulation.

2.1 Nature and General Properties of Enzymes

2.1.1 Definition and nature of enzymes

Enzymes are biological catalysts, nearly all of which are proteins (though a small class of catalytic RNA molecules called ribozymes also exists), that accelerate the rate of specific chemical reactions without themselves being consumed or permanently altered in the process; they achieve this by lowering the activation energy required for the reaction to proceed, allowing reactions to occur at the temperatures and conditions found within living cells.

As proteins, enzymes possess the four levels of structure described for proteins generally, and their catalytic activity depends critically on the precise three-dimensional shape maintained by this structure; denaturation of an enzyme by heat, extreme pH, or chemical agents disrupts this shape and destroys catalytic activity, even though the primary amino acid sequence remains intact, illustrating that enzyme function is inseparable from enzyme conformation.

Fill in the blank: Enzymes are biological ________ that lower the activation energy of specific reactions, allowing them to proceed at the temperatures found within living cells.

2.1.2 General characteristics of enzymes

The general characteristics of enzymes are: they are specific, each enzyme catalysing only one particular reaction or a narrow class of closely related reactions (specificity arising from the precise complementary shape and chemistry of the active site and substrate); they are efficient, increasing reaction rates by factors of many millions compared to uncatalysed rates; they are not consumed by the reaction, emerging unchanged to catalyse additional reaction cycles; and they are required only in very small amounts relative to the substrate they act upon.

Enzymes are also sensitive to environmental conditions: small changes in temperature, pH, ionic strength, or the presence of inhibitory substances can substantially alter enzyme activity, making enzyme regulation a powerful mechanism for controlling metabolic flux within cells; this sensitivity, while requiring careful physiological regulation to maintain, also provides the basis for the precise, responsive control of metabolism discussed later in this Series.

Fill in the blank: Enzymes are ________ , each catalysing only one particular reaction or a narrow class of closely related reactions, due to the precise complementary shape and chemistry of the active site.

2.1.3 Enzyme nomenclature and classification

Enzymes are systematically named and classified by the International Union of Biochemistry and Molecular Biology (IUBMB) according to the type of reaction they catalyse, divided into six major classes: oxidoreductases (catalysing oxidation-reduction reactions), transferases (catalysing transfer of a chemical group from one molecule to another), hydrolases (catalysing hydrolysis reactions, breaking bonds by adding water), lyases (catalysing non-hydrolytic bond breaking or formation), isomerases (catalysing isomerisation reactions), and ligases (catalysing bond formation coupled to ATP hydrolysis).

In common usage, individual enzymes are typically named by adding the suffix -ase to the name of the substrate or the reaction type (for example, amylase catalyses starch hydrolysis, lipase catalyses lipid hydrolysis, and lactase catalyses lactose hydrolysis); some older enzyme names, such as pepsin, trypsin, and rennin, predate the systematic naming convention and remain in widespread use for historical reasons.

Fill in the blank: ________ are the class of enzymes that catalyse hydrolysis reactions, breaking bonds by adding water to the substrate.

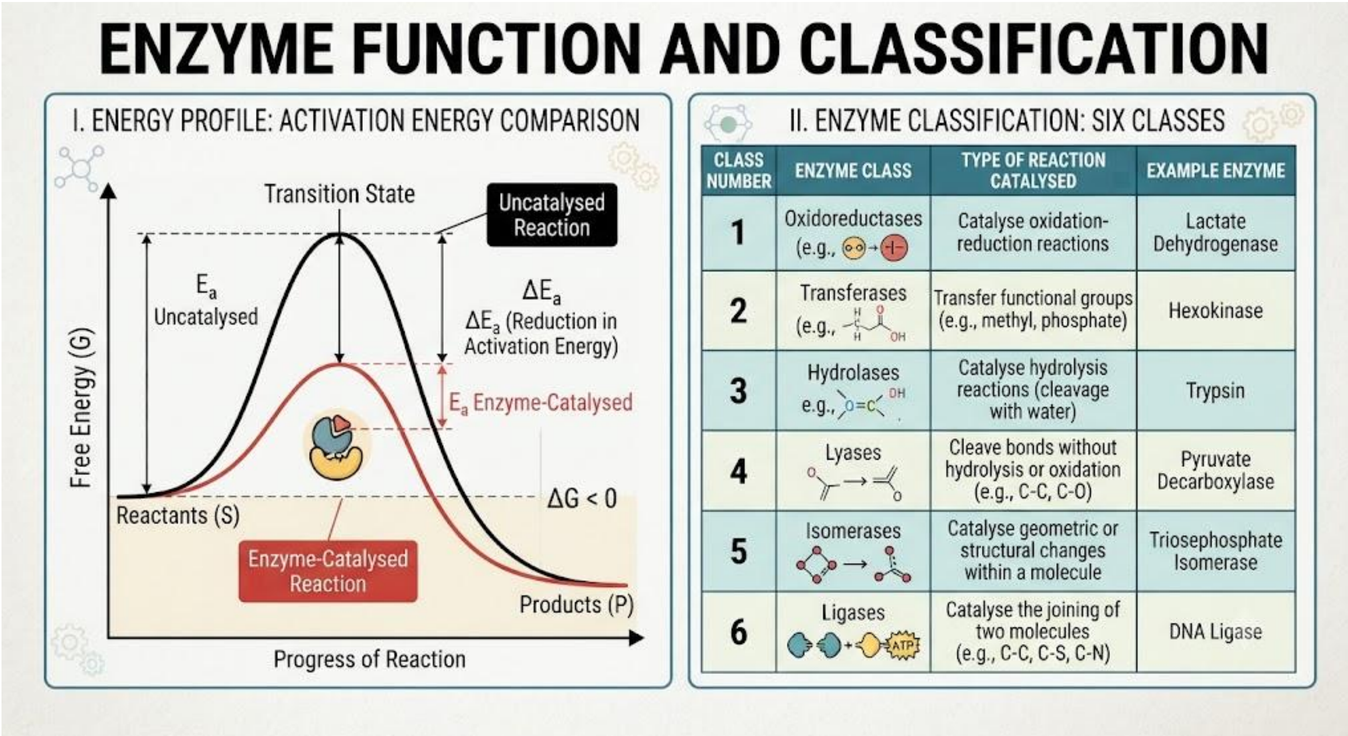

Figure 2.1: Nature and classification of enzymes

Pilot questions 2.1

6. Define enzyme and state their chemical nature.
7. Explain how enzymes lower activation energy.
8. Name four general characteristics of enzymes.
9. Name the six major classes of enzymes and the reaction type each catalyses.
10. Explain the naming convention used for most enzymes.

2.2 Enzyme Structure and the Active Site

2.2.1 Enzyme structure

Enzymes are globular proteins, typically ranging from a few hundred to several thousand amino acids in length, folded into a precise three-dimensional conformation that is essential for catalytic activity; some enzymes consist of a single polypeptide chain (monomeric enzymes), while others are oligomeric, composed of two or more polypeptide subunits held together by non-covalent interactions, with the subunit arrangement forming part of the enzyme quaternary structure described for proteins generally.

The overall enzyme three-dimensional structure creates a specific region within or on the enzyme surface called the active site, where the substrate binds and the catalytic reaction occurs; the remaining portions of the enzyme structure serve to maintain the correct active site geometry, provide structural stability, and, in regulated enzymes, contain additional regulatory binding sites (allosteric sites) at locations separate from the active site itself.

Fill in the blank: The ________ site is the specific region within or on the enzyme surface where the substrate binds and the catalytic reaction occurs.

2.2.2 The active site and enzyme-substrate interaction

The active site is a three-dimensional cleft or pocket formed by a relatively small number of amino acid residues (typically 3 to 10 out of the total enzyme sequence) whose side chains provide the binding contacts and the catalytic groups responsible for the reaction; the shape and chemical complementarity between the active site and the specific substrate molecule determines enzyme specificity, ensuring that only the correct substrate (or closely related molecules) can bind productively.

Two models describe enzyme-substrate interaction: the lock and key model (proposed by Emil Fischer, suggesting the active site has a rigid, pre-formed shape perfectly complementary to the substrate, like a lock fitting only the right key) and the induced fit model (proposed by Daniel Koshland, suggesting the active site is somewhat flexible and changes shape upon substrate binding, with the active site moulding itself around the substrate to achieve optimal complementarity and catalytic positioning, now considered the more accurate model for most enzymes).

Fill in the blank: The induced fit model proposes that the active site is flexible and ________ shape upon substrate binding, moulding itself around the substrate for optimal complementarity.

2.2.3 Cofactors and coenzymes

Many enzymes require additional non-protein components for full catalytic activity, called cofactors; inorganic cofactors are metal ions (such as zinc in carbonic anhydrase, iron in cytochromes, and magnesium in many phosphate-transferring enzymes) that assist catalysis through their charge, coordination chemistry, or redox properties; the enzyme without its cofactor is called an apoenzyme (inactive), while the complete, active enzyme with its cofactor is called a holoenzyme.

Organic cofactors are called coenzymes; most coenzymes are derived from vitamins (such as NAD+/NADH derived from niacin/vitamin B3, FAD/FADH2 derived from riboflavin/vitamin B2, and coenzyme A derived from pantothenic acid/vitamin B5), explaining why vitamin deficiencies can cause widespread metabolic dysfunction; coenzymes typically function as carriers of specific chemical groups or electrons between different enzymatic reactions, linking individual enzyme-catalysed steps into coordinated metabolic pathways.

Fill in the blank: An ________ is an enzyme without its cofactor (inactive), while the complete active enzyme with its cofactor is called a holoenzyme.

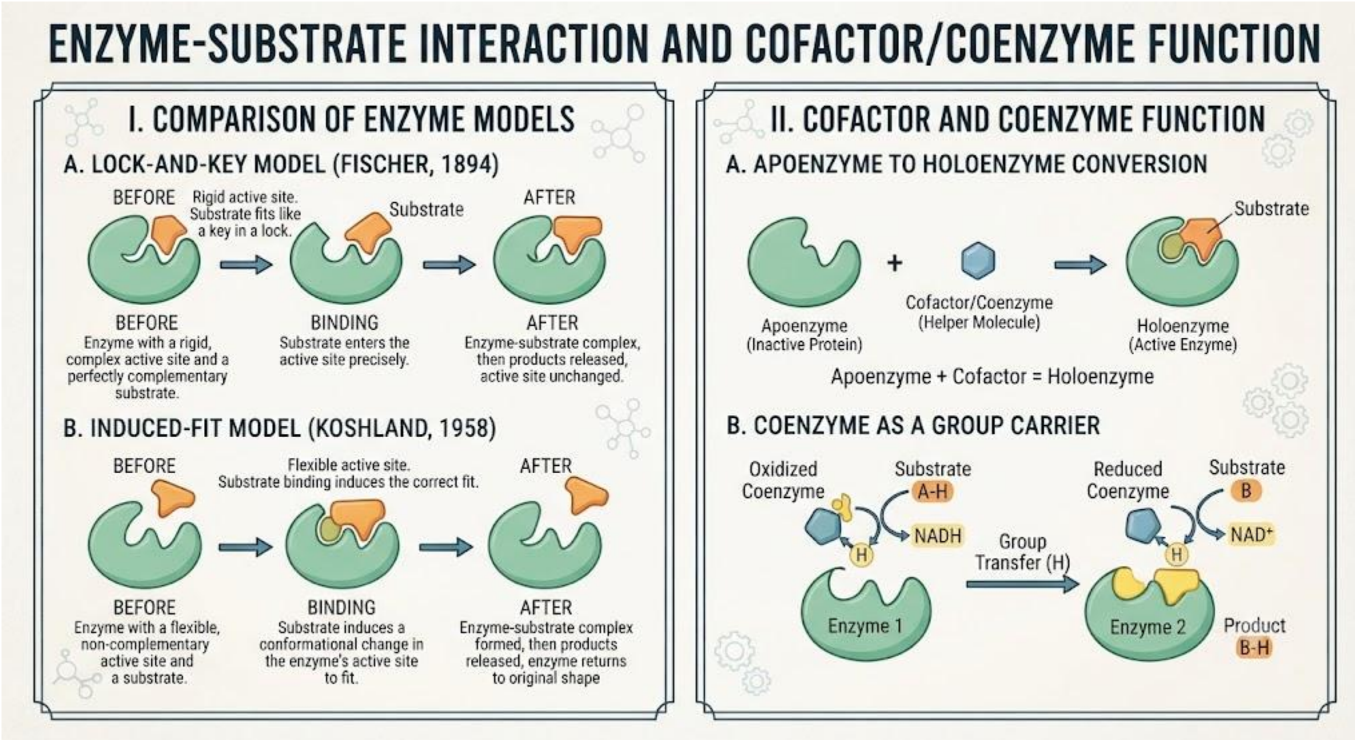

Figure 2.2: Enzyme structure, active site, and cofactors

Pilot questions 2.2

6. Describe the active site of an enzyme.
7. Distinguish between the lock and key model and the induced fit model of enzyme-substrate interaction.
8. Define cofactor, apoenzyme, and holoenzyme.
9. Distinguish between inorganic cofactors and coenzymes.
10. Explain why vitamin deficiencies can cause widespread metabolic dysfunction.

2.3 Factors Affecting Enzyme Activity

2.3.1 Effect of temperature

Enzyme activity generally increases with rising temperature up to an optimum temperature, since higher temperatures increase the kinetic energy of both enzyme and substrate molecules, increasing the frequency of productive collisions between enzyme and substrate; above the optimum temperature, activity decreases rapidly as the enzyme begins to denature, with the increased thermal energy disrupting the non-covalent interactions (hydrogen bonds, ionic interactions, hydrophobic interactions) that maintain the active site geometry.

The optimum temperature for most human enzymes is close to body temperature (approximately 37 degrees Celsius), while enzymes from heat-adapted organisms (thermophiles) may have optima above 70 degrees Celsius; below the optimum, reaction rates fall due to reduced molecular kinetic energy rather than denaturation, making low-temperature enzyme inhibition reversible, while inhibition above the optimum through denaturation is typically irreversible.

Fill in the blank: Above the optimum temperature, enzyme activity decreases as the enzyme begins to ________ , with thermal energy disrupting the non-covalent interactions maintaining active site geometry.

2.3.2 Effect of pH

Each enzyme has a characteristic optimum pH at which its activity is maximal; departures from this optimum in either direction reduce activity, since the ionisation state of the amino acid side chains within the active site, which determines both substrate binding and catalytic activity, depends on the pH of the surrounding solution; most human intracellular enzymes have optima near physiological pH (approximately 7.0 to 7.4), though there are notable exceptions such as pepsin (optimum pH approximately 2) in the acidic stomach environment.

Extreme pH values (well above or below the optimum) can denature the enzyme by disrupting the ionic interactions and hydrogen bonds that maintain its three-dimensional structure, making denaturation through extreme pH largely irreversible just as heat denaturation is; at moderately non-optimal pH values, the effect is reversible upon returning to the optimum pH, since only the ionisation states are altered rather than the primary structure.

Fill in the blank: Most human intracellular enzymes have a pH optimum near ________ , though pepsin in the acidic stomach has an optimum of approximately pH 2.

2.3.3 Effect of substrate concentration and enzyme concentration

At constant enzyme concentration, increasing substrate concentration initially increases reaction rate proportionally (since more substrate means more productive enzyme-substrate collisions), but the rate eventually plateaus at a maximum velocity (Vmax) when all available enzyme active sites are saturated with substrate and the rate becomes limited by how quickly each active site can complete its catalytic cycle and release product; this relationship produces the characteristic hyperbolic Michaelis-Menten curve when reaction velocity is plotted against substrate concentration.

The Michaelis constant (Km) is the substrate concentration at which the reaction proceeds at half its maximum velocity, providing a measure of enzyme-substrate affinity: a low Km indicates high affinity (the enzyme reaches half-maximal velocity at a low substrate concentration) while a high Km indicates low affinity; at constant substrate concentration, reaction rate increases proportionally with increasing enzyme concentration, since more enzyme means more available active sites.

Fill in the blank: The ________ constant (Km) is the substrate concentration at which reaction velocity is half the maximum, providing a measure of enzyme-substrate affinity.

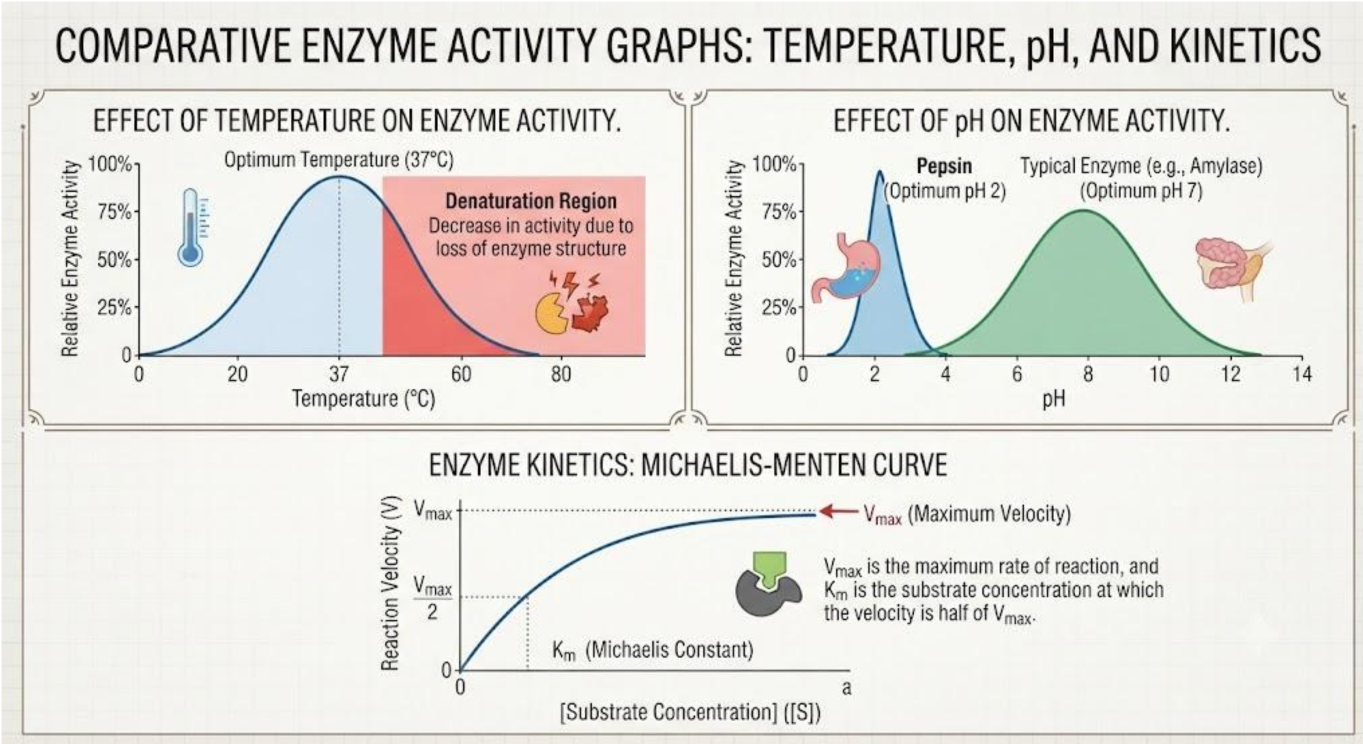

Figure 2.3: Factors affecting enzyme activity

Pilot questions 2.3

6. Explain why enzyme activity increases with temperature up to the optimum.
7. Explain why enzyme activity decreases above the optimum temperature.
8. Explain why each enzyme has a characteristic optimum pH.
9. Describe the shape of the reaction velocity versus substrate concentration curve and explain why it plateaus.
10. Define Km and explain what a low Km value indicates about enzyme-substrate affinity.

2.4 Enzyme Inhibition and Regulation

2.4.1 Competitive inhibition

Competitive inhibition occurs when an inhibitor molecule structurally resembles the substrate and competes with the substrate for binding at the active site, occupying the active site when bound and thereby preventing substrate binding; because the inhibitor and substrate compete for the same site, the degree of inhibition depends on the relative concentrations of inhibitor and substrate, and the inhibition can be overcome by increasing substrate concentration sufficiently to outcompete the inhibitor for active site occupancy.

Competitive inhibition increases the apparent Km of the enzyme (since more substrate is needed to achieve half-maximal velocity when the active site is partly occupied by inhibitor) but does not change the maximum velocity Vmax (since at saturating substrate concentrations the inhibitor is effectively displaced); many medically important drugs work through competitive inhibition, including statins (competitive inhibitors of HMG-CoA reductase in cholesterol synthesis) and many antibiotic and antiviral agents.

Fill in the blank: Competitive inhibition increases the apparent ________ of the enzyme but does not change Vmax, since at saturating substrate concentrations the inhibitor is displaced.

2.4.2 Non-competitive inhibition

Non-competitive inhibition occurs when an inhibitor binds to a site on the enzyme other than the active site (an allosteric site), causing a conformational change in the enzyme that reduces catalytic activity without directly blocking substrate binding; because the inhibitor does not compete with the substrate for the active site, increasing substrate concentration cannot overcome non-competitive inhibition, distinguishing it experimentally and conceptually from competitive inhibition.

Non-competitive inhibition reduces Vmax (since even substrate-bound enzyme is less active when the non-competitive inhibitor is also bound) but does not change Km (since substrate binding affinity is unaffected); uncompetitive inhibition is a related type in which the inhibitor binds only to the enzyme-substrate complex rather than to free enzyme, reducing both Vmax and Km; irreversible inhibitors (such as organophosphate nerve agents that covalently modify the active site serine of acetylcholinesterase) cannot be overcome by any concentration of substrate.

Fill in the blank: Non-competitive inhibition reduces ________ but does not change Km, because the inhibitor does not compete with substrate for the active site.

2.4.3 Allosteric regulation and feedback inhibition

Allosteric regulation is a broader mechanism by which the binding of a regulatory molecule (an allosteric effector, which may be either an activator or an inhibitor) at a site other than the active site causes a conformational change that increases or decreases enzyme activity; allosteric enzymes often display sigmoidal (S-shaped) rather than hyperbolic reaction velocity curves, reflecting cooperative interactions between multiple subunits where binding of the allosteric effector to one subunit influences the activity of others.

Feedback inhibition is a specific and physiologically important form of allosteric regulation in which the end product of a metabolic pathway acts as an allosteric inhibitor of an enzyme early in the same pathway, automatically slowing down production of the end product when it accumulates in sufficient quantity; this self-regulating mechanism prevents the wasteful overproduction of metabolic end products and maintains metabolite concentrations within appropriate physiological ranges.

Fill in the blank: Feedback inhibition occurs when the ________ product of a metabolic pathway acts as an allosteric inhibitor of an enzyme early in the same pathway, slowing its own production.

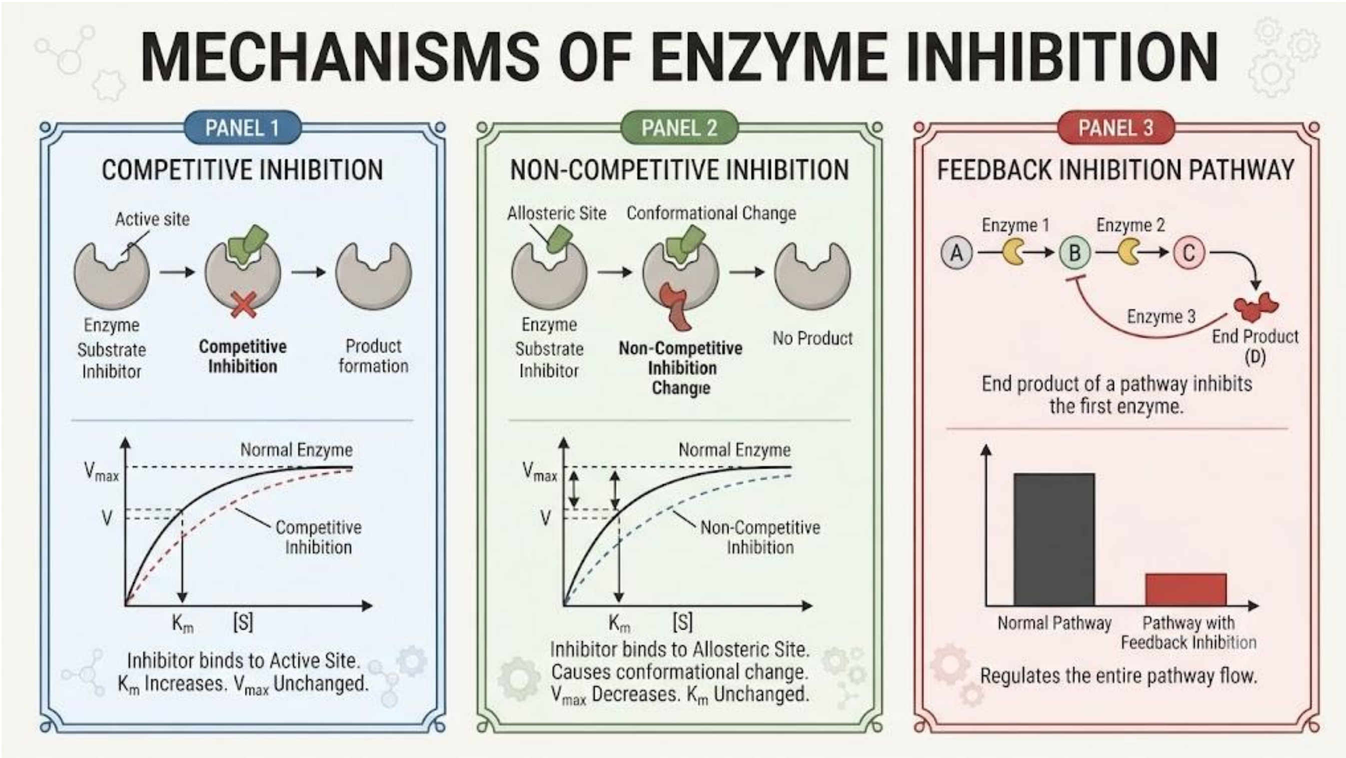

Figure 2.4: Enzyme inhibition and allosteric regulation

Pilot questions 2.4

6. Define competitive inhibition and explain how it can be overcome.
7. Explain the effect of competitive inhibition on Km and Vmax.
8. Define non-competitive inhibition and explain why it cannot be overcome by increasing substrate concentration.
9. Explain the effect of non-competitive inhibition on Km and Vmax.
10. Describe feedback inhibition and explain its physiological significance.

Series Summary

This Series introduced **enzymes** as biological catalysts that regulate and accelerate biochemical reactions in living organisms. You explored their nature, properties, classification, and structure, including the active site, enzyme specificity, and the lock-and-key and induced-fit models of enzyme action. The Series also explained the roles of cofactors, coenzymes, apoenzymes, and holoenzymes in supporting enzyme function.

Building on these concepts, the Series examined the factors that influence enzyme activity, including temperature, pH, and substrate concentration, as well as the principles of enzyme kinetics. You also learned how enzymes are regulated through competitive and non-competitive inhibition and feedback inhibition to maintain efficient metabolic control. By completing this Series, you should now be able to explain enzyme structure and function, analyse the factors affecting enzyme activity, distinguish between major forms of enzyme inhibition, and describe how enzyme regulation controls metabolic pathways, thereby achieving all four **Series Learning Outcomes (SLOs 2.1 to 2.4)**.

Glossary of Terms

- **Allosteric regulation:** regulation of enzyme activity by a molecule binding at a site other than the active site, causing a conformational change.
- **Apoenzyme:** an enzyme without its required cofactor; inactive.
- **Coenzyme:** an organic cofactor, usually derived from a vitamin, required for enzyme activity.
- **Competitive inhibition:** inhibition by a molecule competing with the substrate for the active site; overcome by increasing substrate concentration.
- **Feedback inhibition:** inhibition of an early pathway enzyme by the pathway end product.
- **Holoenzyme:** a complete, active enzyme together with its cofactor.
- **Km (Michaelis constant):** the substrate concentration at which reaction velocity is half the maximum; a measure of enzyme-substrate affinity.

Concept Check Questions [Series 2]

Objective Questions

1. Enzymes lower the ________ energy of reactions, allowing them to proceed at physiological temperatures. (Linked to SLO 2.1)
2. The ________ fit model proposes the active site changes shape upon substrate binding. (Linked to SLO 2.2)
3. Above the optimum temperature, enzyme activity decreases due to ________ of the enzyme. (Linked to SLO 2.3)
4. Competitive inhibition increases apparent ________ but does not change Vmax. (Linked to SLO 2.4)
5. Feedback inhibition occurs when the end ________ of a pathway inhibits an early enzyme in the same pathway. (Linked to SLO 2.4)

Short-Answer Questions

1. Name four general characteristics of enzymes. (Linked to SLO 2.1)
2. Distinguish between the lock and key model and the induced fit model. (Linked to SLO 2.2)
3. Define Km and explain what a low Km value indicates. (Linked to SLO 2.3)
4. Distinguish between competitive and non-competitive inhibition. (Linked to SLO 2.4)
5. Name the six classes of enzymes. (Linked to SLO 2.1)

Long-Answer Questions

1. Describe the nature, general properties, and classification of enzymes. (Linked to SLO 2.1)
2. Explain enzyme structure, the active site, cofactors, and coenzymes. (Linked to SLO 2.2)
3. Explain the effects of temperature, pH, and substrate concentration on enzyme activity, and describe inhibition and regulation. (Linked to SLOs 2.3, 2.4)

Answers to Concept Check Questions [Series 2]

Objective Questions

1. Activation.
2. Induced.
3. Denaturation.
4. Km.
5. Product.

Short-Answer Questions

1. Specific, efficient, not consumed by the reaction, and required in very small amounts.
2. Lock and key: rigid active site pre-formed for the substrate. Induced fit: active site flexible, changes shape to accommodate the substrate.
3. Km is the substrate concentration at half-maximal velocity; a low Km indicates high enzyme-substrate affinity.
4. Competitive inhibition binds the active site and is overcome by more substrate; non-competitive binds elsewhere and cannot be overcome by substrate.
5. Oxidoreductases, transferases, hydrolases, lyases, isomerases, and ligases.

Long-Answer Questions

1. Enzymes are protein biological catalysts that lower activation energy. They are specific, efficient, unchanged, and small-quantity. Classified into six classes (oxidoreductases, transferases, hydrolases, lyases, isomerases, ligases) and named by substrate/reaction type with -ase suffix.
2. Enzymes are globular proteins with an active site (3-10 residues) where substrate binds. Induced fit is the accepted model. Cofactors (metal ions) and coenzymes (vitamin-derived) are required by many enzymes; without cofactors the apoenzyme is inactive; the complete holoenzyme is active.
3. Temperature: activity rises to optimum then falls with denaturation. pH: each enzyme has an optimum; extremes cause denaturation. Substrate concentration: hyperbolic Michaelis-Menten curve; Vmax and Km define kinetics. Competitive inhibition (Km up,

Vmax unchanged) is overcome by substrate; non-competitive (Vmax down, Km unchanged) is not. Feedback inhibition self-regulates metabolic pathways.

Answers to Pilot Questions [Series 2]

Part 2.1

1. An enzyme is a biological catalyst, nearly all of which are proteins, that accelerates specific reactions without being consumed.
2. By lowering the activation energy required for the reaction to proceed.
3. Specific, efficient, not consumed by the reaction, and sensitive to environmental conditions.
4. Oxidoreductases (redox), transferases (group transfer), hydrolases (hydrolysis), lyases (non-hydrolytic bond breaking), isomerases (isomerisation), ligases (bond formation with ATP).
5. The suffix -ase is added to the substrate or reaction type name (e.g. amylase for starch hydrolysis).

Part 2.2

1. The active site is a three-dimensional cleft or pocket formed by a small number of amino acid residues where the substrate binds and the catalytic reaction occurs.
2. Lock and key: the active site is rigid and pre-formed. Induced fit: the active site is flexible and changes shape upon substrate binding.
3. A cofactor is a non-protein component required for enzyme activity; an apoenzyme is inactive without it; a holoenzyme is the active enzyme-cofactor complex.
4. Inorganic cofactors are metal ions; coenzymes are organic molecules, typically vitamin-derived.
5. Coenzymes are derived from vitamins; without adequate vitamins, coenzymes cannot be made, disabling the enzyme-catalysed reactions that depend on them.

Part 2.3

1. Higher temperature increases kinetic energy of molecules, increasing the frequency of productive enzyme-substrate collisions.
2. Above the optimum, thermal energy disrupts non-covalent interactions maintaining active site geometry, causing denaturation and loss of activity.
3. The ionisation state of active site amino acid residues depends on pH; departure from the optimum alters these states, reducing substrate binding and catalytic activity.
4. The curve is hyperbolic, rising then plateauing at Vmax when all active sites are saturated with substrate.
5. Km is the substrate concentration at half-maximal velocity; a low Km indicates high affinity (the enzyme achieves half Vmax at a low substrate concentration).

Part 2.4

1. Competitive inhibition: an inhibitor binds the active site competing with substrate; overcome by increasing substrate concentration to outcompete the inhibitor.
2. Competitive inhibition increases apparent Km (more substrate needed) but leaves Vmax unchanged.
3. Non-competitive inhibition: inhibitor binds an allosteric site, causing conformational change; substrate concentration cannot overcome it since the active site is unblocked.
4. Non-competitive inhibition decreases Vmax but leaves Km unchanged.
5. Feedback inhibition: end product inhibits an early pathway enzyme allosterically; it prevents overproduction of the end product and maintains metabolite concentrations within appropriate ranges.

References and Attributions

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Figure 2.1: Nature and classification of enzymes Attribution: AI generated. Suggested OER search string: "enzyme activation energy classification oxidoreductase hydrolase diagram biology OER".
- Figure 2.2: Enzyme structure, active site, and cofactors Attribution: AI generated. Suggested OER search string: "enzyme active site lock key induced fit cofactor coenzyme apoenzyme holoenzyme diagram OER".
- Figure 2.3: Factors affecting enzyme activity Attribution: AI generated. Suggested OER search string: "enzyme activity temperature pH substrate concentration Michaelis Menten Km Vmax graph OER".
- Figure 2.4: Enzyme inhibition and allosteric regulation Attribution: AI generated. Suggested OER search string: "competitive non-competitive inhibition allosteric feedback inhibition enzyme diagram biology OER".

Course code: BIO 203

Course title: General Physiology

Course credit load: 2 Units

Series 3: Nutrition, Digestion, and Absorption

- **Part 3.1: Nutrition in Plants**
  - Sub Part 3.1.1: Autotrophic nutrition and photosynthesis
  - Sub Part 3.1.2: Mineral nutrition in plants
  - Sub Part 3.1.3: Nitrogen fixation and the nitrogen cycle
- **Part 3.2: Nutrition in Animals**
  - Sub Part 3.2.1: Types of animal nutrition and nutrients
  - Sub Part 3.2.2: Balanced diet and nutritional disorders
  - Sub Part 3.2.3: Vitamins and minerals in animal nutrition
- **Part 3.3: Digestion in Animals**
  - Sub Part 3.3.1: Types of digestion
  - Sub Part 3.3.2: Human alimentary canal and digestive organs
  - Sub Part 3.3.3: Digestive enzymes and their actions
- **Part 3.4: Absorption and Assimilation**
  - Sub Part 3.4.1: Absorption in the small intestine
  - Sub Part 3.4.2: Role of the large intestine
  - Sub Part 3.4.3: Assimilation and fate of absorbed nutrients

Introduction

Nutrition encompasses all the processes by which organisms obtain, process, and utilise the substances required for energy, growth, and the maintenance of normal physiological function. Plants and animals differ fundamentally in their nutritional strategies: plants manufacture their own organic nutrients through photosynthesis (autotrophic nutrition), while animals must obtain pre-formed organic nutrients by consuming other organisms (heterotrophic nutrition) and then digest these into absorbable forms.

This Series examines plant nutrition, including photosynthesis and mineral requirements; animal nutrition, including nutrient types, balanced diet, and vitamins and minerals; the process of digestion in animals, including the human alimentary canal and digestive enzymes; and the absorption of digested nutrients and their assimilation into the body. This physiological knowledge builds directly on the organic chemistry and enzyme biochemistry covered in the earlier Series of this course.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 3.1** describe autotrophic nutrition in plants, including photosynthesis, mineral nutrition, and nitrogen fixation,
- **SLO 3.2** describe animal nutrition, including nutrient types, balanced diet, and the roles of vitamins and minerals,
- **SLO 3.3** describe the process of digestion in animals, including the human alimentary canal and digestive enzymes, and
- **SLO 3.4** explain absorption in the small intestine, the role of the large intestine, and the assimilation of absorbed nutrients.

3.1 Nutrition in Plants

3.1.1 Autotrophic nutrition and photosynthesis

Plants are autotrophs, capable of synthesising all their organic compounds from simple inorganic raw materials using an external energy source; in photoautotrophs (which include all green plants), the energy source is sunlight captured by the green pigment chlorophyll within chloroplasts, and the raw materials are carbon dioxide (from air, entering through stomata) and water (from the soil, absorbed through roots), with oxygen released as a by-product.

Photosynthesis proceeds in two major stages: the light-dependent reactions (occurring in the thylakoid membranes, where light energy is used to split water molecules, releasing oxygen, and to produce the energy carriers ATP and NADPH) and the light-independent reactions or Calvin cycle (occurring in the stroma, where ATP and NADPH are used to fix carbon dioxide into organic carbon compounds, ultimately producing glucose); the overall equation is: 6CO2 + 6H2O + light energy yields C6H12O6 + 6O2.

Fill in the blank: Photosynthesis occurs in two stages: light-dependent reactions in the thylakoid membranes and light-independent reactions (the Calvin cycle) in the ________ .

3.1.2 Mineral nutrition in plants

Beyond carbon, hydrogen, and oxygen (obtained from CO2 and water), plants require a range of mineral elements absorbed from the soil in ionic form through root hair cells; macronutrients (required in relatively larger amounts) include nitrogen (as nitrate or ammonium ions, essential for amino acid, protein, and nucleic acid synthesis), phosphorus (as phosphate ions, essential for nucleotides, ATP, and membrane phospholipids), potassium, calcium, magnesium (central atom of chlorophyll), and sulphur.

Micronutrients (trace elements required in very small amounts) include iron (for cytochrome electron carriers and chlorophyll synthesis), manganese, zinc, copper, molybdenum, and boron; deficiency of any essential mineral element produces characteristic deficiency symptoms reflecting the disrupted function (nitrogen deficiency causes yellowing of leaves due to chlorophyll breakdown, phosphorus deficiency causes purpling of leaves, and iron deficiency causes chlorosis with green veins on yellowing leaves).

Fill in the blank: Magnesium is a macronutrient required in relatively larger amounts; it forms the central atom of ________ and is essential for photosynthesis.

3.1.3 Nitrogen fixation and the nitrogen cycle

Although nitrogen gas (N2) makes up approximately 78 percent of the atmosphere, most plants cannot use it directly and depend on soil nitrogen in the form of nitrate or ammonium ions; nitrogen fixation is the conversion of atmospheric N2 into ammonia (NH3) or ammonium ions (NH4+) by nitrogen-fixing bacteria, including free-living soil bacteria such as Azotobacter and symbiotic bacteria such as Rhizobium, which form nodules on the roots of leguminous plants and have a mutually beneficial relationship with the host plant.

The nitrogen cycle describes the continuous movement of nitrogen through the atmosphere, soil, and living organisms: nitrogen fixation adds nitrogen to the biological pool; nitrification (by nitrifying bacteria) converts ammonium to nitrate; denitrification (by denitrifying bacteria) returns nitrogen to the atmosphere; decomposition releases nitrogen from organic matter back to the soil; and assimilation incorporates inorganic nitrogen into organic compounds within plants and animals, completing the cycle.

Fill in the blank: Rhizobium bacteria form nodules on the roots of ________ plants, fixing atmospheric nitrogen in a mutually beneficial symbiotic relationship with the host.

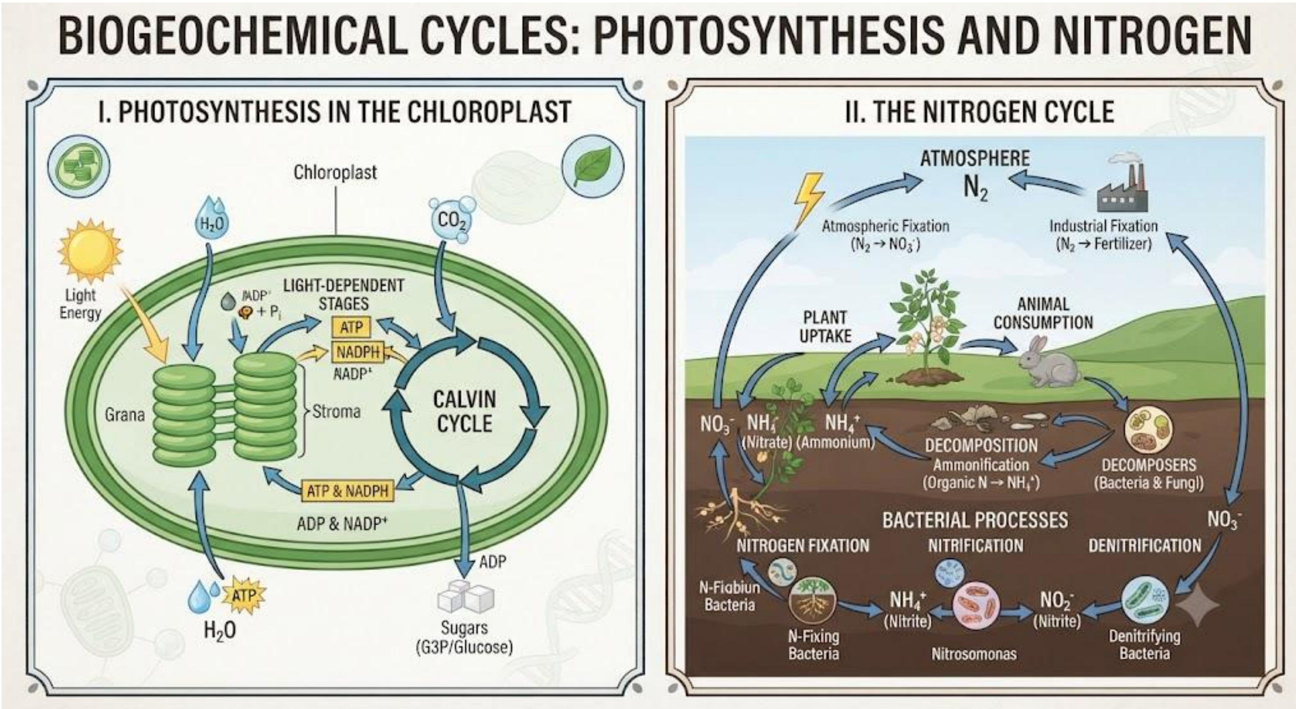


Figure 3.1: Plant nutrition and the nitrogen cycle

Pilot questions 3.1

11. Define autotrophic nutrition.
12. State the overall equation for photosynthesis.
13. Distinguish between the light-dependent reactions and the Calvin cycle.
14. Name three macronutrients required by plants and state the role of each.
15. Describe the role of Rhizobium in the nitrogen cycle.

3.2 Nutrition in Animals

3.2.1 Types of animal nutrition and nutrients

Animals are heterotrophs, obtaining organic nutrients by consuming other organisms; they are classified by feeding strategy: herbivores consume plants, carnivores consume other animals, and omnivores consume both; at the biochemical level, the nutrients animals require are divided into macronutrients (carbohydrates, lipids, and proteins, needed in relatively large amounts for energy and structural purposes) and micronutrients (vitamins and minerals, needed in smaller amounts for regulatory and metabolic roles).

Water, while not often classified as a nutrient in the traditional sense, is the most immediately essential substance for animal survival, since even a relatively small loss of body water (dehydration) severely impairs physiological function; the six nutrient classes for animals are therefore water, carbohydrates, lipids, proteins, vitamins, and minerals, each with specific functions that cannot be substituted by another nutrient class.

Fill in the blank: Animals are ________ , obtaining organic nutrients by consuming other organisms, classified as herbivores, carnivores, or omnivores based on feeding strategy.

3.2.2 Balanced diet and nutritional disorders

A balanced diet provides all essential nutrients in the correct proportions to maintain health, growth, and normal physiological function: it must supply sufficient energy (from carbohydrates and fats) to meet metabolic demands, adequate protein (containing all essential amino acids) for growth and tissue maintenance, sufficient vitamins and minerals for regulatory functions, dietary fibre (aiding gut motility and preventing constipation), and adequate water for hydration.

Nutritional disorders arise from dietary imbalances: undernutrition (inadequate total energy intake) causes marasmus (severe wasting) or kwashiorkor (protein deficiency with oedema); overnutrition (excess energy intake) leads to obesity and associated metabolic diseases including type 2 diabetes and cardiovascular disease; specific micronutrient deficiencies cause characteristic diseases such as scurvy (vitamin C deficiency), rickets (vitamin D/calcium deficiency), anaemia (iron or vitamin B12 deficiency), and goitre (iodine deficiency).

Fill in the blank: Kwashiorkor is a nutritional disorder caused by ________ deficiency, characterised by oedema, while marasmus results from severely inadequate total energy intake.

3.2.3 Vitamins and minerals in animal nutrition

Vitamins are organic micronutrients required in small amounts that the animal body cannot synthesise in sufficient quantity from other dietary components and must therefore obtain from food; fat-soluble vitamins (A, D, E, and K) are stored in fatty tissues and the liver and can accumulate to toxic levels if consumed in excess, while water-soluble vitamins (B complex and C) are not stored effectively and must be consumed regularly, with excess generally excreted in urine.

Essential minerals include macrominerals (calcium for bones, teeth, and muscle/nerve function; phosphorus for bones and ATP/nucleotides; sodium and potassium for nerve impulse transmission and osmotic balance; iron for haemoglobin oxygen transport; magnesium for enzyme cofactor roles) and trace minerals (zinc, copper, selenium, iodine, and others required in very small amounts for specific enzymatic and metabolic functions); mineral deficiencies produce specific, often serious physiological consequences reflecting the disrupted function.

Fill in the blank: Fat-soluble vitamins (A, D, E, and K) are stored in fatty tissues and the liver and can accumulate to ________ levels if consumed in excess, unlike water-soluble vitamins.

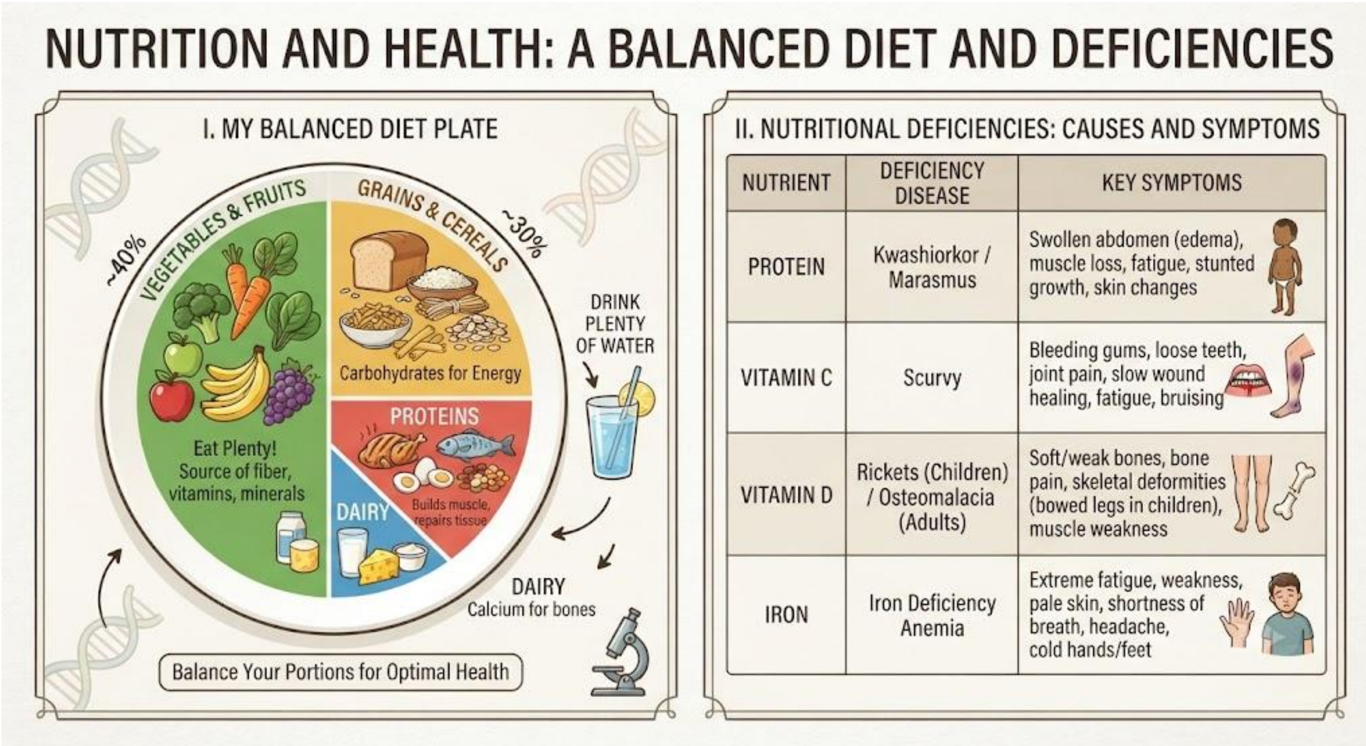


Figure 3.2: Animal nutrition, balanced diet, and vitamins/minerals

Pilot questions 3.2

1. Define heterotrophic nutrition and name three types of animal feeding strategy.
2. State five components of a balanced diet.
3. Distinguish between marasmus and kwashiorkor.
4. Distinguish between fat-soluble and water-soluble vitamins in terms of storage and toxicity risk.
5. Name two minerals essential for bone formation and two for nerve function.

3.3 Digestion in Animals

3.3.1 Types of digestion

Digestion is the breakdown of complex ingested food molecules into smaller, simpler, soluble molecules that can be absorbed across the gut wall; it occurs through two complementary processes: mechanical digestion (physical breakdown of food into smaller pieces by chewing in the mouth, churning in the stomach, and muscular gut movements, increasing the surface area available for chemical digestion without changing the chemical nature of the food molecules) and chemical digestion (enzymatic hydrolysis of large food molecules, breaking glycosidic bonds in carbohydrates, peptide bonds in proteins, and ester bonds in lipids, producing monosaccharides, amino acids, fatty acids, and glycerol respectively).

Extracellular digestion (digestion outside the cells, within the lumen of the digestive tract, as in most animals including humans) is the main mode in complex animals, allowing digestion of much larger food items than would be possible through intracellular digestion; intracellular digestion (digestion within cells, in lysosomes, after phagocytosis of food particles, as in Amoeba and as a supplementary mechanism in some animal tissues) is the more ancestral mode found in simpler organisms.

Fill in the blank: Chemical digestion uses enzymatic ________ to break large food molecules into absorbable units, breaking glycosidic, peptide, and ester bonds.

3.3.2 Human alimentary canal and digestive organs

The human alimentary canal is a continuous tube running from the mouth to the anus, comprising the mouth and salivary glands, oesophagus, stomach, small intestine (duodenum, jejunum, and ileum), large intestine (colon and rectum), and anus; associated digestive organs include the liver (producing bile, stored in the gall bladder, which emulsifies fats) and the pancreas (producing a range of digestive enzymes and bicarbonate secreted into the duodenum via the pancreatic duct).

The stomach is a muscular, J-shaped organ that stores and mixes food with gastric juice (containing hydrochloric acid, which denatures proteins and activates pepsinogen to pepsin, and mucus, which protects the stomach lining from acid self-digestion), producing chyme; the small intestine, the principal site of chemical digestion and absorption, has a greatly increased surface area for absorption through the folds of the mucosa (plicae circulares), finger-like villi, and microscopic microvilli on the epithelial cells (the brush border), together increasing absorptive surface area by approximately 600-fold.

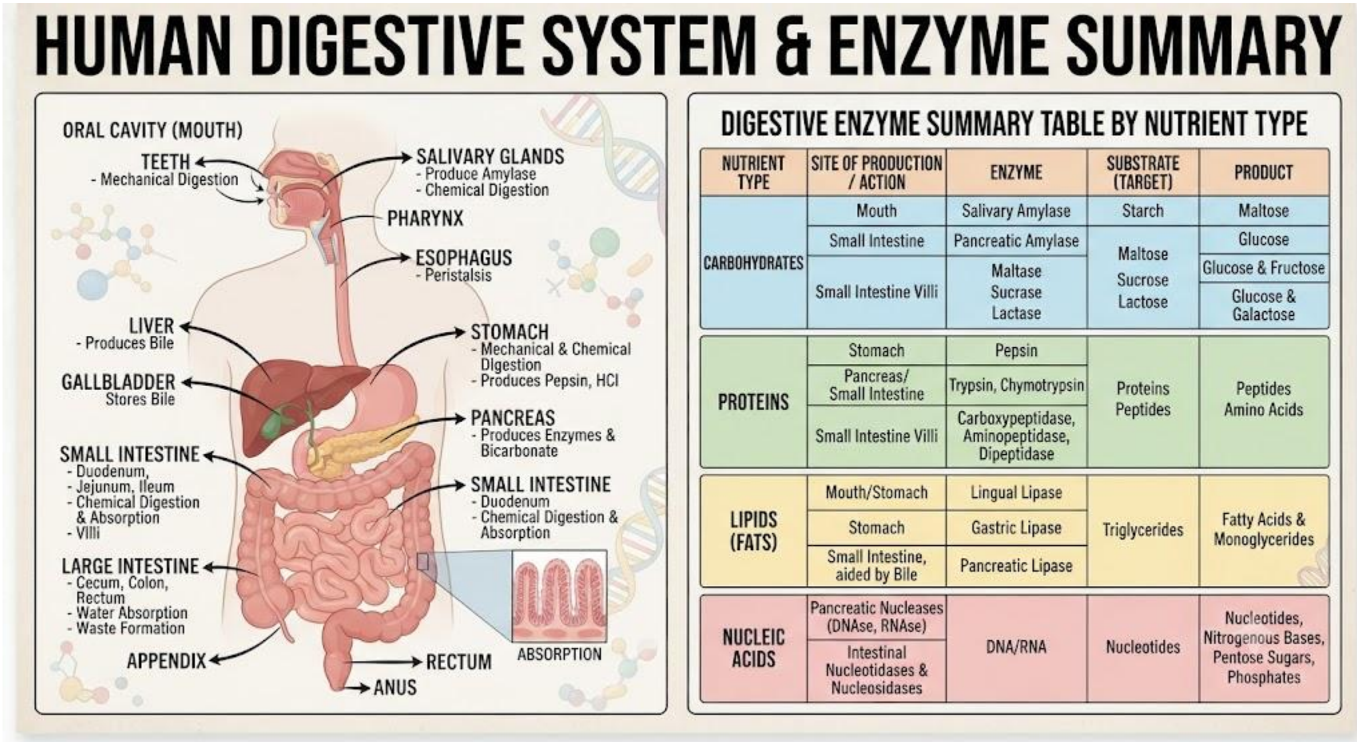
Fill in the blank: The liver produces ________ , stored in the gall bladder and secreted into the duodenum, which emulsifies dietary fats for enzymatic digestion.

3.3.3 Digestive enzymes and their actions

Digestion of carbohydrates begins in the mouth with salivary amylase (breaking starch to maltose) and continues in the small intestine with pancreatic amylase (further breaking starch to maltose) and brush border enzymes including maltase, sucrase, and lactase (completing disaccharide hydrolysis to monosaccharides); protein digestion begins in the stomach with pepsin (active under acidic conditions, cleaving peptide bonds) and continues in the small intestine with trypsin, chymotrypsin, and elastase (all secreted by the pancreas as inactive zymogens activated in the duodenum) and then peptidases completing the breakdown to amino acids.

Lipid digestion occurs primarily in the small intestine, where bile salts emulsify fat globules into smaller droplets (increasing surface area for enzyme action), and pancreatic lipase then hydrolyses triglycerides into fatty acids and monoglycerides; many digestive enzymes are secreted as inactive precursor forms (zymogens or proenzymes), such as pepsinogen, trypsinogen, and chymotrypsinogen, activated only in the correct digestive environment to prevent self-digestion of the secretory cells and organs.

Fill in the blank: Many digestive enzymes are secreted as inactive precursor forms called ________ , activated only in the correct digestive environment to prevent self-digestion.



NUTRIENT TYPE	SITE OF PRODUCTION / ACTION	ENZYME	SUBSTRATE (TARGET)	PRODUCT
CARBOHYDRATES	Mouth	Salivary Amylase	Starch	Maltose
	Small Intestine	Pancreatic Amylase	Maltose Sucrose Lactose	Glucose
	Small Intestine Villi	Maltase Sucrase Lactase		Glucose & Fructose
				Glucose & Galactose
PROTEINS	Stomach	Pepsin	Proteins Peptides	Peptides Amino Acids
	Pancreas/ Small Intestine	Trypsin, Chymotrypsin		
	Small Intestine Villi	Carboxypeptidase, Aminopeptidase, Dipeptidase		
LIPIDS (FATS)	Mouth/Stomach	Lingual Lipase	Triglycerides	Fatty Acids & Monoglycerides
	Stomach	Gastric Lipase		
	Small Intestine, aided by Bile	Pancreatic Lipase		
NUCLEIC ACIDS	Pancreatic Nucleases (DNAse, RNAse) Intestinal Nucleotidases & Nucleosidases	DNA/RNA	Nucleotides	Nucleotides, Nitrogenous Bases, Pentose Sugars, Phosphates

Figure 3.3: Human digestion

Pilot questions 3.3

1. Distinguish between mechanical and chemical digestion.
2. Name the sections of the human small intestine.
3. Explain the function of bile in fat digestion.
4. Name two digestive enzymes acting on proteins and state where each acts.
5. Explain why many digestive enzymes are secreted as zymogens.

3.4 Absorption and Assimilation

3.4.1 Absorption in the small intestine

Absorption is the movement of digested nutrient molecules from the lumen of the alimentary canal across the intestinal epithelium into the blood or lymph; the small intestine is the principal site of absorption, its efficiency supported by its immense surface area (from villi, microvilli, and intestinal folds), rich blood supply (bringing absorbed molecules rapidly to the liver via the hepatic portal vein), and the variety of transport mechanisms available to the epithelial cells.

Monosaccharides (glucose, galactose) and amino acids are absorbed primarily by active transport against a concentration gradient, co-transported with sodium ions (secondary active transport); fatty acids and monoglycerides (from fat digestion) are absorbed by diffusion across the lipid membrane of the epithelial cells, then reassembled into triglycerides, packaged with cholesterol and protein into lipoprotein particles called chylomicrons, and transported into the lacteal (the central lymph vessel of each villus) rather than directly into the blood capillaries.

Fill in the blank: Fatty acids and monoglycerides are reassembled into triglycerides in the intestinal epithelial cells, packaged as ________ , and transported into the lacteal lymph vessel.

3.4.2 Role of the large intestine

The large intestine (colon) receives undigested material, dietary fibre, water, and electrolytes from the small intestine; its primary functions are the reabsorption of water and electrolytes (converting liquid chyme into semi-solid faeces), providing a habitat for the gut microbiome (a large and diverse community of bacteria that ferment undigested carbohydrates, synthesise certain vitamins including vitamin K and some B vitamins, and protect against colonisation by pathogenic organisms), and the temporary storage of faeces prior to defecation.

The gut microbiome of the large intestine has become increasingly recognised as playing important roles beyond digestion, with evidence linking microbiome composition to immune function, mental health, and the risk of various metabolic and inflammatory diseases; disruption of the microbiome (dysbiosis) through antibiotic use, dietary changes, or disease can have wide-ranging physiological consequences, reflecting the extent to which the human body and its resident microbial community have co-evolved.

Fill in the blank: The primary functions of the large intestine are reabsorption of water and electrolytes, housing the gut ________ , and temporary storage of faeces.

3.4.3 Assimilation and fate of absorbed nutrients

Assimilation is the incorporation of absorbed nutrients into the body tissues and metabolic processes; absorbed monosaccharides and amino acids pass from the small intestine into the hepatic portal vein and travel directly to the liver, which regulates blood glucose levels (converting excess glucose to glycogen for storage, or to fat for longer-term storage), removes toxic substances, synthesises plasma proteins, and converts excess amino acids through deamination, with the nitrogen excreted as urea.

Absorbed fatty acids enter the blood circulation via the lymphatic system (after chylomicron transport through the lacteal to the thoracic duct and then to the bloodstream), where they are transported to tissues for oxidation as energy fuel or stored as triglycerides in adipose tissue; the fate of absorbed nutrients thus depends on the current metabolic state of the body, with nutrients directed toward energy production during fasting or exercise and toward storage and anabolic processes (growth, repair) after feeding.

Fill in the blank: Excess amino acids undergo ________ in the liver, with the nitrogen-containing group removed and excreted as urea.

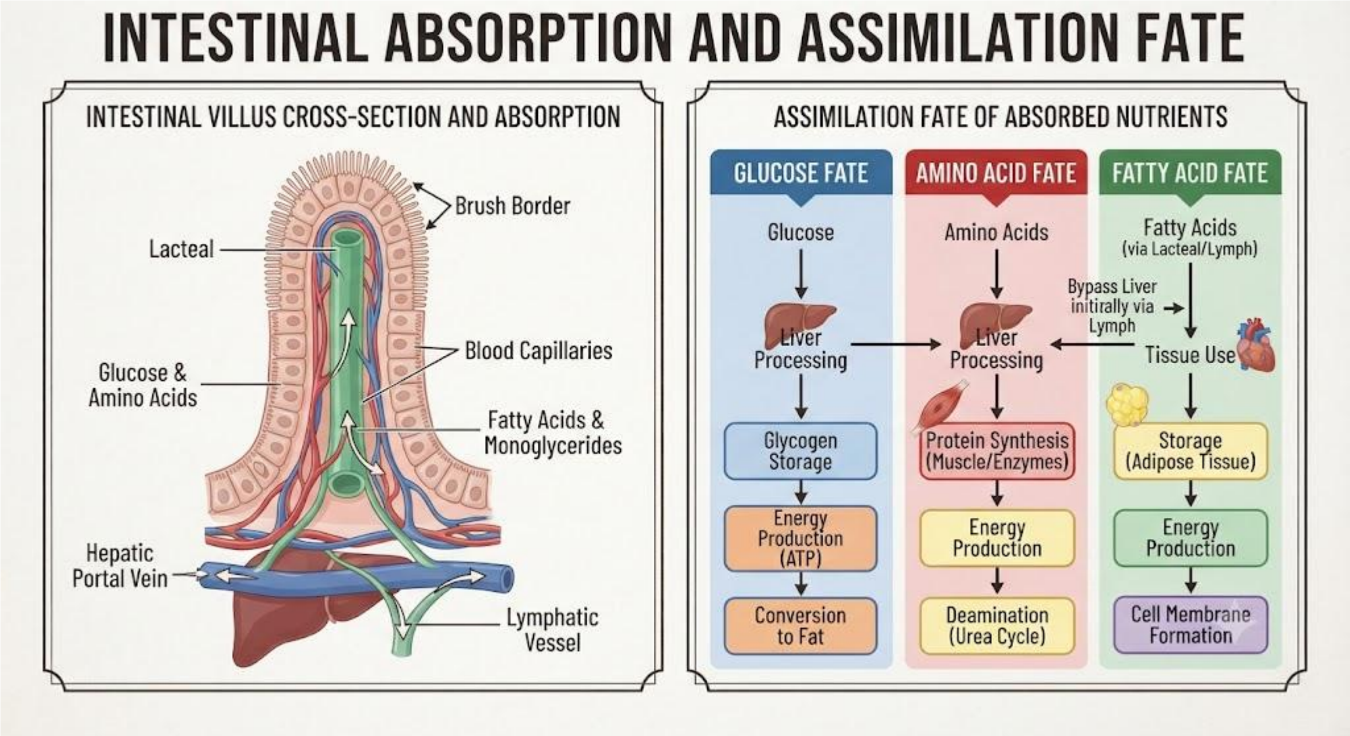


Figure 3.4: Absorption and assimilation of nutrients

Pilot questions 3.4

1. Define absorption and state the principal site of absorption in the human digestive system.
2. Explain how monosaccharides and amino acids are absorbed across the intestinal epithelium.
3. Explain why fat absorption products enter the lymphatic system rather than the blood capillaries directly.
4. Name three functions of the large intestine.
5. Explain the role of the liver in the assimilation of absorbed glucose and amino acids.

Series Summary

This Series explored **nutrition in plants and animals**, highlighting how living organisms obtain, process, and utilise nutrients to sustain life. You examined photoautotrophic nutrition in plants through photosynthesis and the nitrogen cycle, as well as heterotrophic nutrition in animals, including the six classes of nutrients, balanced diets, and the causes and effects of nutritional deficiencies and excesses.

Building on these foundations, the Series explained the processes of digestion, absorption, and assimilation in animals, covering the structure and functions of the alimentary canal, accessory organs, digestive enzymes, and nutrient absorption in the small intestine. You also learned how absorbed nutrients are transported, processed, stored, or used by the body. By completing this Series, you should now be able to explain plant and animal nutrition, describe the processes of digestion, absorption, and assimilation, relate nutrient functions to health and metabolism, and apply these concepts to biological systems, thereby achieving all four **Series Learning Outcomes (SLOs 3.1 to 3.4)**.

Glossary of Terms

- **Assimilation:** the incorporation of absorbed nutrients into body tissues and metabolic processes.
- **Chylomicron:** a lipoprotein particle transporting reassembled triglycerides from intestinal epithelial cells into the lymphatic system.
- **Emulsification:** the physical breakdown of fat globules into smaller droplets by bile salts, increasing surface area for lipase action.
- **Hepatic portal vein:** the blood vessel carrying absorbed nutrients from the small intestine directly to the liver.
- **Lacteal:** the central lymph vessel of an intestinal villus, receiving chylomicrons from fat absorption.

- **Nitrogen fixation:** the conversion of atmospheric N2 into ammonia or ammonium ions by nitrogen-fixing bacteria.
- **Zymogen:** an inactive enzyme precursor activated only in the correct digestive environment.

Concept Check Questions [Series 3]

Objective Questions

1. Photosynthesis light-independent reactions (the Calvin cycle) occur in the ________ of the chloroplast. (Linked to SLO 3.1)
2. ________ is a nutritional disorder caused by protein deficiency, characterised by oedema. (Linked to SLO 3.2)
3. Bile is produced by the ________ and stored in the gall bladder before secretion into the duodenum. (Linked to SLO 3.3)
4. Fat absorption products are packaged as ________ and transported into the lacteal lymph vessel. (Linked to SLO 3.4)
5. Many digestive enzymes are secreted as inactive ________ to prevent self-digestion. (Linked to SLO 3.3)

Short-Answer Questions

1. Distinguish between the light-dependent reactions and the Calvin cycle. (Linked to SLO 3.1)
2. Name five components of a balanced diet. (Linked to SLO 3.2)
3. Explain the function of bile in fat digestion. (Linked to SLO 3.3)
4. Explain how monosaccharides are absorbed in the small intestine. (Linked to SLO 3.4)
5. Name three functions of the large intestine. (Linked to SLO 3.4)

Long-Answer Questions

1. Describe plant nutrition, including photosynthesis, mineral requirements, and nitrogen fixation. (Linked to SLO 3.1)

2. Describe animal nutrition and the process of digestion in the human digestive system. (Linked to SLOs 3.2, 3.3)
3. Explain absorption in the small intestine and the assimilation of absorbed nutrients. (Linked to SLO 3.4)

Answers to Concept Check Questions [Series 3]

Objective Questions

1. Stroma.
2. Kwashiorkor.
3. Liver.
4. Chylomicrons.
5. Zymogens.

Short-Answer Questions

1. Light-dependent reactions occur in thylakoids and produce ATP and NADPH using light; the Calvin cycle occurs in the stroma and uses ATP and NADPH to fix CO_2 into glucose.
2. Carbohydrates, proteins, fats, vitamins, minerals, and water (any five).
3. Bile emulsifies fat globules into smaller droplets, increasing surface area for pancreatic lipase action.
4. Monosaccharides are absorbed by secondary active transport, co-transported with sodium ions, across the epithelial brush border into the blood capillaries.
5. Water and electrolyte reabsorption, housing the gut microbiome, and temporary storage of faeces before defecation.

Long-Answer Questions

1. Plants are photoautotrophs using sunlight, CO_2, and water to produce glucose via photosynthesis (light-dependent in thylakoids, Calvin cycle in stroma). Plants absorb mineral macronutrients (N, P, K, Mg) and micronutrients from the soil. Nitrogen fixation by Rhizobium converts N_2 to usable nitrogen, part of the broader nitrogen cycle.
2. Animals are heterotrophs needing balanced diets (carbohydrates, proteins, fats, vitamins, minerals, water); deficiencies cause kwashiorkor, scurvy, rickets, anaemia. Digestion in the alimentary canal involves mechanical breakdown and chemical hydrolysis by amylase, pepsin, trypsin, and lipase; bile emulsifies fats; zymogens prevent self-digestion.
3. The small intestine absorbs monosaccharides and amino acids by active transport into blood capillaries and the hepatic portal vein; fats enter as chylomicrons via the lacteal and lymph. The liver regulates glucose and amino acids; excess amino acids are deaminated and urea excreted. Fats are stored in adipose tissue or oxidised for energy.

Answers to Pilot Questions [Series 3]

Part 3.1

1. Autotrophic nutrition is the synthesis of all organic compounds from simple inorganic raw materials using an external energy source.
2. $6CO_2 + 6H_2O$ + light energy yields $C_6H_{12}O_6 + 6O_2$.
3. Light-dependent reactions use light energy in thylakoids to produce ATP and NADPH; the Calvin cycle uses these to fix CO_2 into glucose in the stroma.
4. Nitrogen (amino acid/protein/nucleic acid synthesis), phosphorus (nucleotides/ATP/membrane phospholipids), and magnesium (central atom of chlorophyll).
5. Rhizobium forms root nodules on legumes, fixing atmospheric N_2 into ammonium in a mutualistic symbiosis.

Part 3.2

1. Heterotrophic nutrition obtains organic nutrients by consuming other organisms; types include herbivore, carnivore, and omnivore.
2. Carbohydrates, proteins, fats, vitamins, minerals, water, and dietary fibre (any five).
3. Marasmus is severe energy deficiency causing wasting; kwashiorkor is protein deficiency causing oedema.
4. Fat-soluble vitamins are stored in fatty tissues and can accumulate to toxic levels; water-soluble vitamins are not stored and must be consumed regularly.
5. Calcium and phosphorus for bone; sodium and potassium for nerve function.

Part 3.3

1. Mechanical digestion physically breaks food into smaller pieces; chemical digestion enzymatically hydrolyses large molecules into absorbable units.
2. Duodenum, jejunum, and ileum.
3. Bile salts emulsify fat globules into smaller droplets, greatly increasing the surface area available for pancreatic lipase action.
4. Pepsin acts in the stomach; trypsin acts in the small intestine (duodenum).
5. Secretion as zymogens (inactive precursors) prevents self-digestion of the secretory cells and organs before activation in the correct digestive environment.

Part 3.4

1. Absorption is the movement of digested nutrients from the gut lumen into blood or lymph; the principal site is the small intestine.
2. Monosaccharides are absorbed by secondary active transport, co-transported with sodium ions, across the brush border into blood capillaries.
3. Fats are packaged into chylomicrons that are too large to enter blood capillaries directly and instead enter the larger lacteal lymph vessel for transport via the lymphatic system.

4. Water and electrolyte reabsorption, housing the gut microbiome, and temporary faeces storage.
5. The liver converts excess glucose to glycogen or fat for storage, regulates blood glucose, synthesises plasma proteins, and deaminates excess amino acids, with the nitrogen excreted as urea.

References and Attributions

Textual References (Books and External Sources)

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- Stryer, L., Berg, J. M., & Tymoczko, J. L. (2015). Biochemistry (8th ed.). W. H. Freeman.
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Figures, Plates, Tables, and Boxes

- Figure 3.1: Plant nutrition and the nitrogen cycle Attribution: AI generated. Suggested OER search string: "photosynthesis light dependent Calvin cycle nitrogen fixation nitrification denitrification cycle diagram OER".
- Figure 3.2: Animal nutrition, balanced diet, and vitamins/minerals Attribution: AI generated. Suggested OER search string: "balanced diet nutritional disorders vitamins minerals deficiency scurvy rickets anaemia diagram OER".
- Figure 3.3: Human digestion Attribution: AI generated. Suggested OER search string: "human digestive system alimentary canal digestive enzymes amylase pepsin lipase diagram OER".
- Figure 3.4: Absorption and assimilation of nutrients Attribution: AI generated. Suggested OER search string: "intestinal villus absorption chylomicron glucose amino acid assimilation hepatic portal vein diagram OER".

Course code: BIO 203

Course title: General Physiology

Course credit load: 2 Units

Series 4: Cell Membrane, Osmoregulation, and Homeostasis

- **Part 4.1: Cell Membrane Structure and Function**
    - Sub Part 4.1.1: The fluid mosaic model
    - Sub Part 4.1.2: Membrane proteins and their functions
    - Sub Part 4.1.3: Membrane transport mechanisms
- **Part 4.2: Osmoregulation**
    - Sub Part 4.2.1: Osmosis and water potential
    - Sub Part 4.2.2: Osmoregulation in animals
    - Sub Part 4.2.3: Osmoregulation in plants
- **Part 4.3: Excretion and Transport in Animals**
    - Sub Part 4.3.1: Excretion and the kidney
    - Sub Part 4.3.2: Blood and transport
    - Sub Part 4.3.3: The lymphatic system
- **Part 4.4: Homeostasis**
    - Sub Part 4.4.1: Principles of homeostasis
    - Sub Part 4.4.2: Temperature regulation
    - Sub Part 4.4.3: Blood glucose regulation

Introduction

The ability of living cells to maintain a distinct internal environment, different from their surroundings, is one of the defining characteristics of life. This capacity depends on the cell membrane as a selective barrier, on the mechanisms of osmoregulation that control water and solute balance, on excretory systems that remove metabolic waste, and on the broader homeostatic mechanisms that maintain the constancy of the internal environment despite continuously changing external conditions.

This Series covers the structure and function of the cell membrane, including the fluid mosaic model and membrane transport; osmoregulation in animals and plants; excretion through the kidney, blood transport, and the lymphatic system; and the principles of homeostasis with specific attention to temperature regulation and blood glucose control.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 4.1** describe the fluid mosaic model of the cell membrane and explain membrane protein functions and transport mechanisms,
- **SLO 4.2** explain osmosis, water potential, and osmoregulation in animals and plants,
- **SLO 4.3** describe excretion through the kidney, blood transport, and the lymphatic system, and
- **SLO 4.4** explain the principles of homeostasis, temperature regulation, and blood glucose regulation.

4.1 Cell Membrane Structure and Function

4.1.1 The fluid mosaic model

The fluid mosaic model (proposed by Singer and Nicolson in 1972) describes the cell membrane as a dynamic structure consisting of a phospholipid bilayer in which the phospholipid molecules are free to move laterally (making the membrane fluid), with a variety of protein molecules embedded within or associated with the bilayer in a mosaic-like, non-uniform distribution; cholesterol molecules interspersed among the phospholipid chains moderate membrane fluidity, preventing it from becoming too rigid at low temperatures or too fluid at high temperatures.

The phospholipid bilayer has its hydrophilic phosphate heads facing outward (toward the aqueous environments on both sides of the membrane) and its hydrophobic fatty acid tails facing inward (forming the hydrophobic core that makes the membrane relatively impermeable to polar and charged molecules); this amphipathic organisation spontaneously forms a bilayer in aqueous environments and provides the fundamental selective permeability that allows the membrane to regulate what enters and exits the cell.

Fill in the blank: In the fluid mosaic model, ________ molecules interspersed among the phospholipids moderate membrane fluidity across temperature changes.

4.1.2 Membrane proteins and their functions

Membrane proteins are classified by their relationship to the bilayer: integral (intrinsic) proteins are embedded within the bilayer, spanning the full thickness of the membrane in the case of transmembrane proteins (which may form channels or carriers for specific molecules), while peripheral (extrinsic) proteins are loosely associated with the membrane surface rather than embedded within it; integral proteins cannot be removed without disrupting the bilayer, while peripheral proteins can be removed more gently.

Membrane proteins carry out diverse and critical functions: channel and carrier proteins facilitate the transport of specific substances across the membrane; receptor proteins bind signalling molecules such as hormones and neurotransmitters on the extracellular surface, triggering intracellular responses; cell recognition glycoproteins (with attached carbohydrate chains) serve as cellular identity markers for immune recognition; enzymatic proteins catalyse reactions at the membrane surface; and structural proteins link the membrane to the cytoskeleton.

Fill in the blank: ________ proteins span the full thickness of the membrane, functioning as channels or carriers for specific molecules crossing the bilayer.

4.1.3 Membrane transport mechanisms

Passive transport mechanisms move substances across the membrane down their concentration or electrochemical gradient without requiring cellular energy: simple diffusion (small non-polar molecules such as O2, CO2, and ethanol crossing the hydrophobic core directly), facilitated diffusion (polar or charged molecules crossing through specific channel or carrier proteins, still down their gradient, as occurs for glucose and ions in many cells), and osmosis (the diffusion of water across a selectively permeable membrane, driven by differences in water potential).

Active transport mechanisms move substances against their concentration or electrochemical gradient, requiring energy (ATP) and specific carrier proteins (pumps); the sodium-potassium pump (Na+/K+-ATPase) is the most abundant animal cell pump, expelling three sodium ions and importing two potassium ions per ATP hydrolysed, maintaining the ionic gradients essential for nerve impulse transmission; bulk transport (endocytosis and exocytosis) moves larger materials across the membrane by membrane vesicle formation, requiring energy but capable of handling materials far larger than individual molecules.

Fill in the blank: The sodium-potassium pump expels ________ sodium ions and imports two potassium ions per ATP hydrolysed, maintaining ionic gradients essential for nerve function.

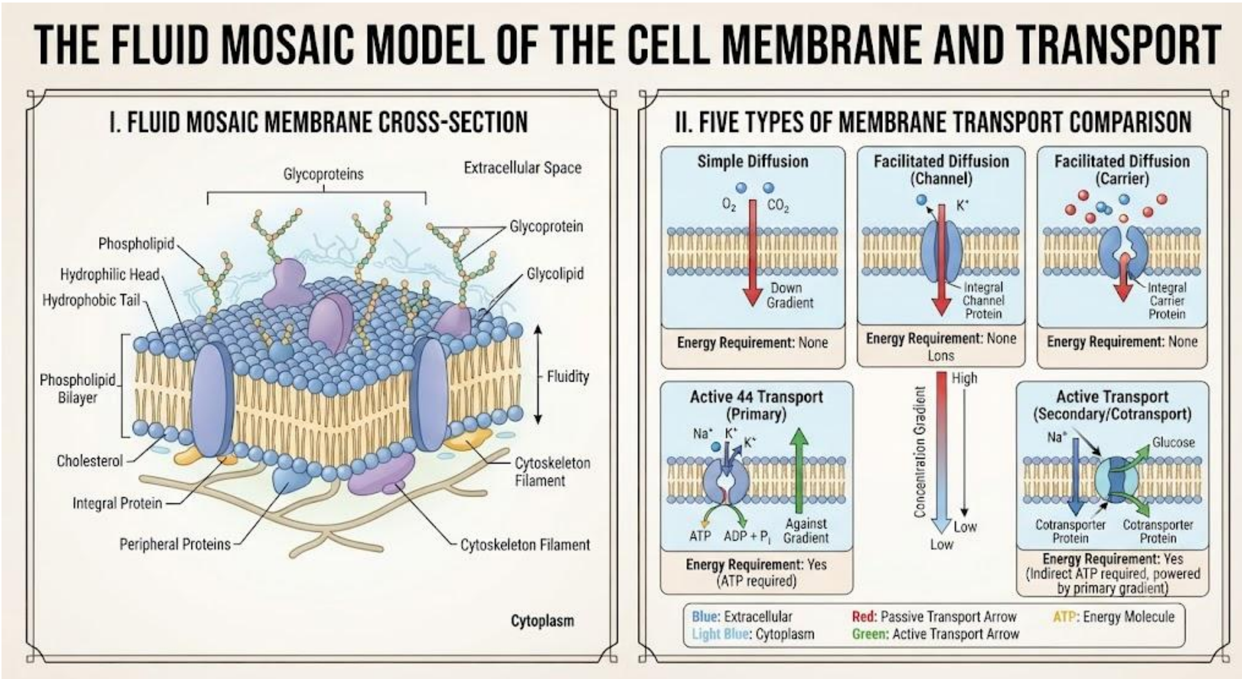

Figure 4.1: Cell membrane structure and transport

Pilot questions 4.1

1. Describe the fluid mosaic model of the cell membrane.
2. Explain the role of cholesterol in the cell membrane.
3. Distinguish between integral and peripheral membrane proteins.
4. Name three functions of membrane proteins.
5. Distinguish between passive and active transport.

4.2 Osmoregulation

4.2.1 Osmosis and water potential

Osmosis is the net movement of water molecules across a selectively permeable membrane from a region of higher water potential to a region of lower water potential; water potential (symbol psi) is a measure of the tendency of water to move from one region to another, with pure water assigned a water potential of zero and solutions having negative water potential values (since dissolved solutes reduce the tendency of water to move).

The water potential of a solution is determined by both the solute concentration (the solute potential, always negative, reducing water potential below zero) and any applied pressure (the pressure potential, which in a plant cell wall can be positive, increasing water potential); when a cell is placed in a solution of higher solute concentration (lower water potential) than the cell contents, water leaves the cell by osmosis, causing the cell to lose volume (plasmolysis in plant cells, crenation in animal cells) until osmotic equilibrium is reached.

Fill in the blank: Pure water has a water potential of ________ , with solutions having negative water potential values because dissolved solutes reduce the tendency of water to move.

4.2.2 Osmoregulation in animals

Osmoregulation is the physiological control of the water and solute content of body fluids, maintaining the internal osmotic environment within the narrow range required for normal cellular function; the primary osmoregulatory organs in mammals are the kidneys (examined in Part 4.3), which adjust the osmolarity and volume of urine in response to the hydration state of the body; animals that maintain a constant internal osmolarity independent of the external environment are called osmoregulators, while those whose internal osmolarity tracks external changes are osmoconformers.

Marine bony fish face the challenge of losing water to their hypertonic (higher solute concentration) seawater environment by osmosis and compensate by drinking large amounts of seawater and excreting small volumes of concentrated urine; freshwater fish face the opposite challenge, gaining water by osmosis from their hypotonic environment and compensate by rarely drinking and excreting large volumes of dilute urine; these contrasting strategies illustrate how different osmotic environments demand fundamentally different osmoregulatory responses.

Fill in the blank: Marine bony fish lose water to their ________ seawater environment and compensate by drinking seawater and producing small volumes of concentrated urine.

4.2.3 Osmoregulation in plants

In plant cells, the cell wall provides a rigid boundary that resists expansion; when a plant cell absorbs water by osmosis (because the cell contents have lower water potential than the surrounding solution), the cell contents expand against the rigid cell wall, generating turgor pressure (the pressure exerted by cell contents against the wall); turgor pressure is important for maintaining plant rigidity in non-woody tissues and for the opening and closing of stomata.

When a plant cell is placed in a hypertonic solution (lower water potential outside), water leaves the cell by osmosis; the cell contents shrink and the plasma membrane pulls away from the cell wall in a process called plasmolysis; the plant wilts as cells lose turgor; plasmolysis is initially reversible if the cell is returned to water, but prolonged severe dehydration causes permanent damage; plants regulate their water potential through root water uptake and the control of water loss through stomata, involving abscisic acid (ABA) signalling examined in detail in the plant growth Series.

Fill in the blank: When a plant cell loses water to a hypertonic solution, the plasma membrane pulls away from the cell wall in a process called ________ .

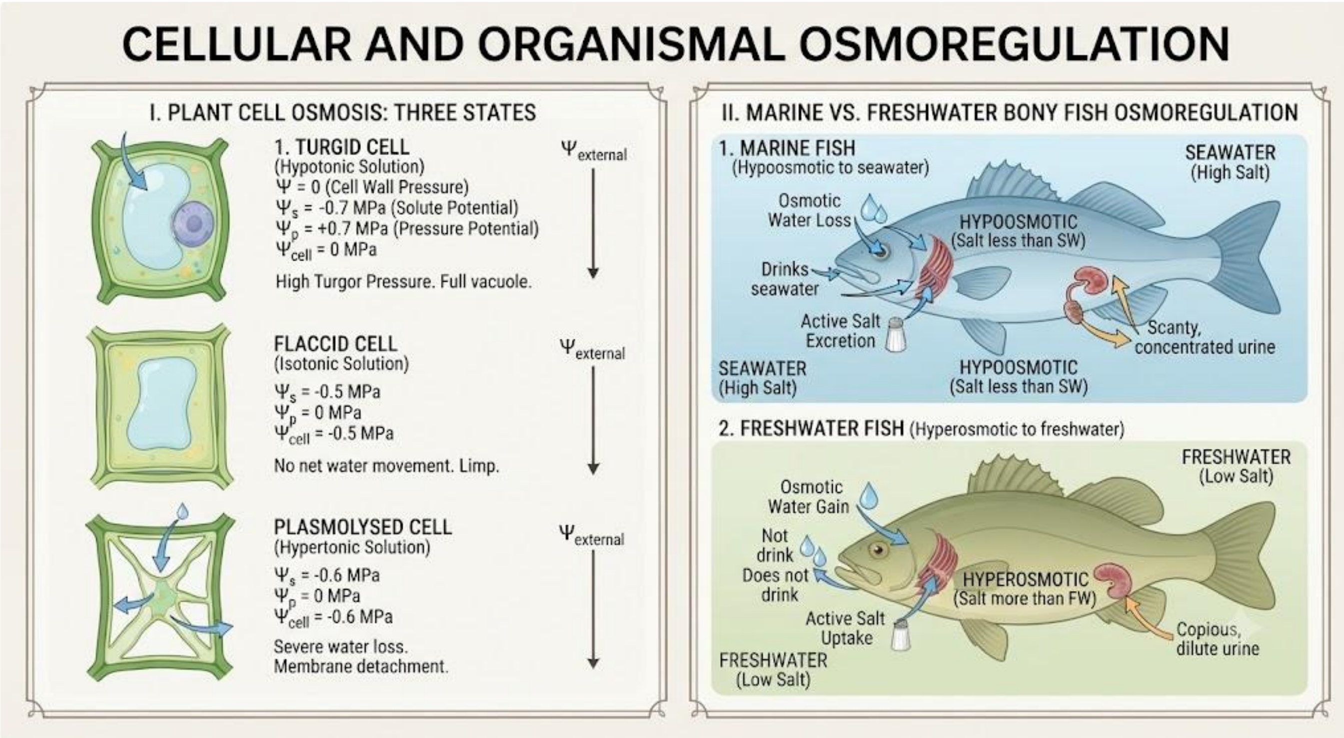

Figure 4.2: Osmosis, water potential, and osmoregulation

Pilot questions 4.2

1. Define osmosis and water potential.
2. Explain what happens when a plant cell is placed in a hypertonic solution.
3. Define turgor pressure and explain its importance.
4. Distinguish between osmoregulators and osmoconformers.
5. Compare osmoregulation in marine and freshwater bony fish.

4.3 Excretion and Transport in Animals

4.3.1 Excretion and the kidney

Excretion is the removal from the body of metabolic waste products produced by normal cellular metabolism, particularly nitrogenous waste from protein and amino acid catabolism (urea in mammals, uric acid in birds and reptiles, ammonia in aquatic invertebrates and fish); the kidney is the primary excretory organ in mammals, each kidney consisting of approximately one million functional units called nephrons, which filter the blood and process the filtrate to produce urine.

Urine formation in the nephron involves three key processes: filtration (blood pressure forces small molecules, including water, glucose, amino acids, urea, and ions, from the glomerular capillaries into the Bowman capsule, forming the glomerular filtrate, while blood cells and large proteins are retained in the blood); selective reabsorption (useful substances including glucose, amino acids, and most water and ions are reabsorbed from the filtrate back into the blood in the proximal tubule, loop of Henle, and distal tubule); and secretion (additional waste products are actively secreted from the blood into the tubule for excretion).

Fill in the blank: Urine formation involves filtration, selective ________ of useful substances back into the blood, and secretion of additional wastes into the tubule.

4.3.2 Blood and transport

Blood is a fluid connective tissue consisting of plasma (the liquid matrix, approximately 55 percent of blood volume, containing water, dissolved proteins, nutrients, hormones, and dissolved gases) and formed elements (red blood cells carrying oxygen via haemoglobin, white blood cells of the immune system, and platelets for clotting); blood is circulated by the heart through arteries (carrying oxygenated blood away from the heart), capillaries (the fine exchange vessels where nutrient and gas exchange with tissues occurs), and veins (returning deoxygenated blood to the heart).

Haemoglobin in red blood cells carries oxygen by reversible binding (forming oxyhaemoglobin in the lungs and releasing oxygen in respiring tissues); carbon dioxide is transported primarily as bicarbonate ions in the plasma (after CO_2 reacts with water to form carbonic acid, catalysed by the enzyme carbonic anhydrase, which then dissociates to bicarbonate and a hydrogen ion) and to a lesser extent in combination with haemoglobin as carbaminohaemoglobin.

Fill in the blank: Carbon dioxide is transported primarily as ________ ions in the plasma, formed when CO_2 reacts with water catalysed by carbonic anhydrase.

4.3.3 The lymphatic system

The lymphatic system is a network of vessels, nodes, and organs complementary to the blood circulatory system; lymphatic capillaries collect excess interstitial fluid (the fluid that leaks from blood capillaries into the tissue spaces), returning it to the blood circulation via the lymph nodes and ultimately the thoracic duct; the lymph also carries fat absorbed from the gut as chylomicrons (from the lacteals of the small intestine), which enter the lymphatic system rather than the blood capillaries.

Lymph nodes are small, bean-shaped structures located along the lymphatic vessels that filter lymph and harbour lymphocytes (a type of white blood cell central to adaptive immune responses), trapping and destroying pathogens and foreign particles before the lymph is returned to the blood; the spleen, thymus, and tonsils are additional lymphoid organs with important immune and lymphocyte development functions, together making the lymphatic system both a fluid drainage and an immune function system.

Fill in the blank: Lymph nodes filter lymph and harbour ________ , white blood cells central to adaptive immune responses, trapping pathogens before lymph returns to the blood.

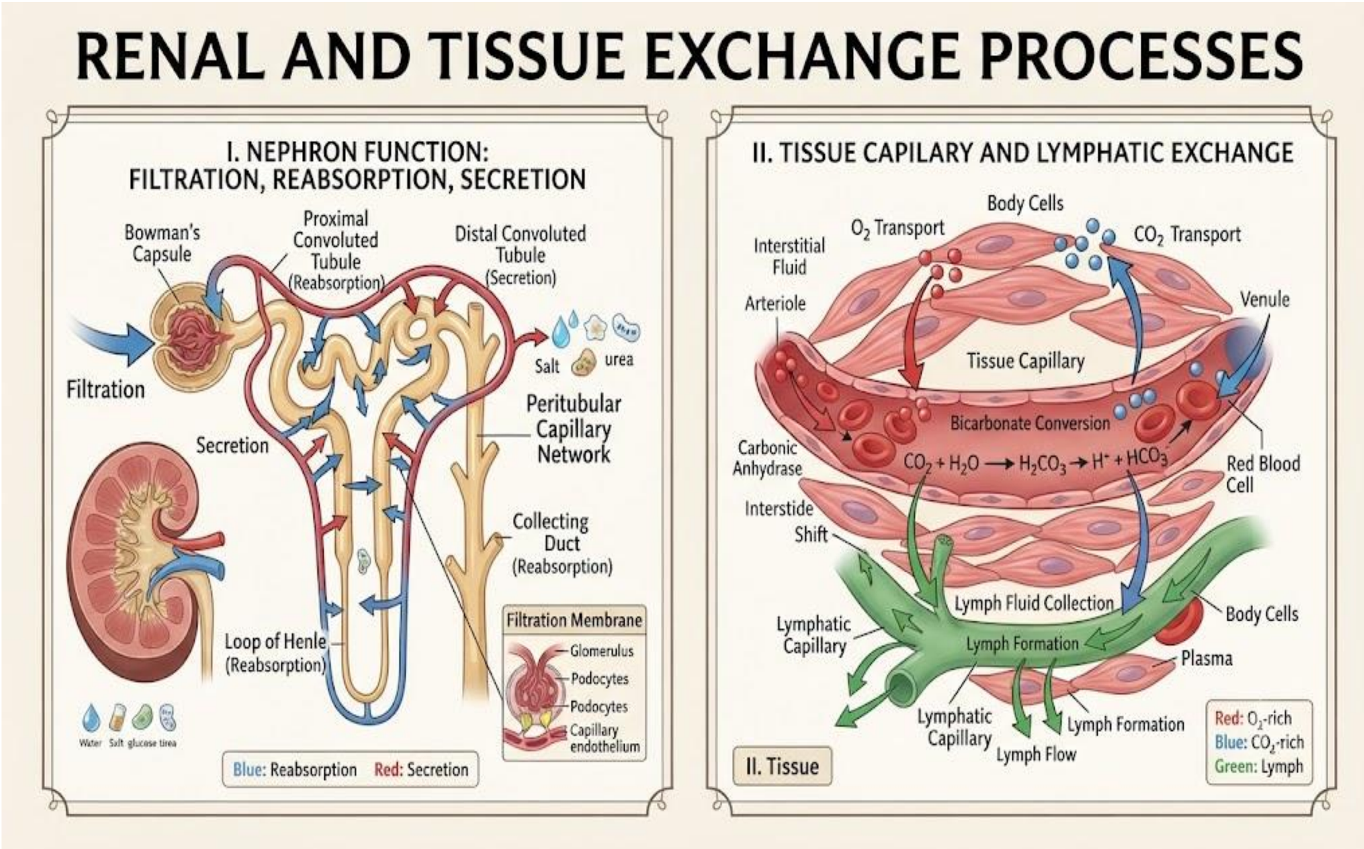

Figure 4.3: Excretion, blood transport, and the lymphatic system

Pilot questions 4.3

1. Define excretion and name the main nitrogenous waste product in mammals.
2. Describe the three processes of urine formation in the nephron.
3. Name the four components of blood and state the function of each.
4. Describe how carbon dioxide is transported in the blood.
5. State two functions of the lymphatic system.

4.4 Homeostasis

4.4.1 Principles of homeostasis

Homeostasis is the maintenance of a relatively stable internal environment (in terms of temperature, pH, blood glucose concentration, osmolarity, and other physiological variables) despite continuously changing external conditions and fluctuating internal metabolic demands; it was first described by Claude Bernard and Walter Cannon and is a fundamental principle of animal physiology, reflecting the narrow range of conditions within which enzymes (highly sensitive to environmental changes) and other physiological processes can function optimally.

Homeostatic regulation operates through negative feedback loops: a receptor (sensor) detects a deviation from the set point (the optimal physiological value for a given variable); this information is transmitted to a control centre (often in the brain) that compares the measured value to the set point and initiates an appropriate corrective response through effectors (muscles, glands, or organs) that act to return the variable toward the set point; once the deviation is corrected, the receptor detects the return to normal and the corrective response is dampened, completing the negative feedback loop.

Fill in the blank: Homeostatic negative feedback loops involve a receptor detecting deviation from the ________ point, a control centre initiating a corrective response through effectors.

4.4.2 Temperature regulation

Endotherms (mammals and birds) maintain a stable body temperature primarily through metabolic heat production and behavioural and physiological responses to temperature change, regardless of external temperature; when body temperature rises above the set point (approximately 37 degrees C in humans), cooling responses are activated: vasodilation (widening of skin blood vessels, increasing heat loss through radiation and convection), sweating (evaporative cooling), and reduced metabolic heat production; when temperature falls, warming responses are activated: vasoconstriction (reducing skin blood flow and heat loss), shivering (increased skeletal muscle activity generating heat), and piloerection (raising of body hair, trapping insulating air).

Ectotherms (reptiles, amphibians, fish, and invertebrates) rely primarily on external heat sources to regulate body temperature, using behavioural thermoregulation (basking in sunlight, seeking shade or burrows) rather than metabolic heat generation; they generally have lower metabolic rates than endotherms at comparable temperatures, but are more vulnerable to environmental temperature extremes and cannot maintain performance at very low temperatures the way endotherms can.

Fill in the blank: When body temperature rises above the set point, cooling responses including ________ of skin blood vessels and sweating are activated to increase heat loss.

4.4.3 Blood glucose regulation

Blood glucose concentration is maintained within a narrow range (approximately 4 to 8 millimoles per litre in humans) by the antagonistic actions of two pancreatic hormones: insulin (secreted by beta cells of the islets of Langerhans when blood glucose rises after a meal) stimulates uptake of glucose by cells (particularly muscle and adipose tissue), promotes conversion of glucose to glycogen in the liver and muscles (glycogenesis), and inhibits glycogen breakdown, collectively lowering blood glucose back toward the set point.

Glucagon (secreted by alpha cells of the islets of Langerhans when blood glucose falls, such as during fasting or exercise) stimulates glycogen breakdown in the liver (glycogenolysis) and gluconeogenesis (the synthesis of new glucose from non-carbohydrate precursors such as amino acids and glycerol), raising blood glucose back toward the set point; diabetes mellitus (type 1, due to autoimmune destruction of beta cells and insulin deficiency; type 2, due to insulin resistance of target cells) disrupts this regulation with serious long-term consequences for multiple organ systems.

Fill in the blank: Glucagon, secreted by ________ cells of the islets of Langerhans, stimulates glycogen breakdown and gluconeogenesis to raise blood glucose toward the set point.

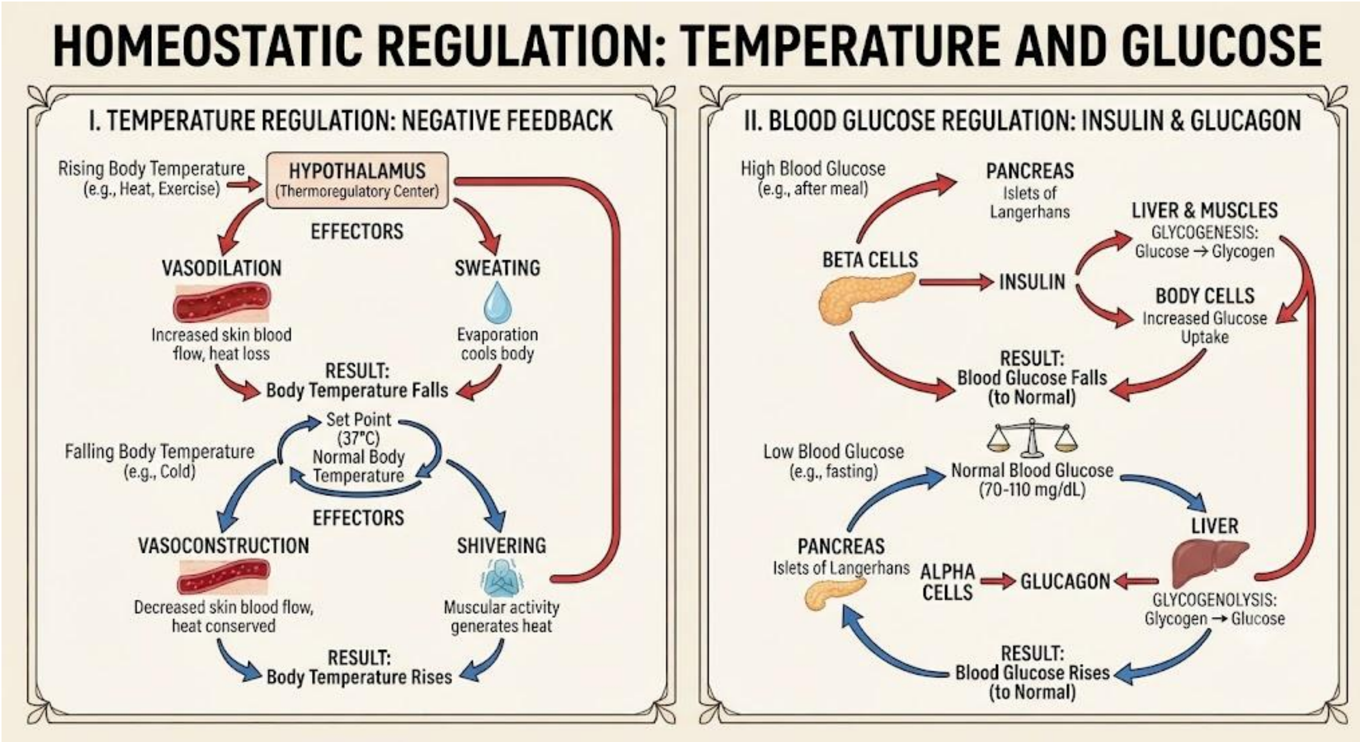

Figure 4.4: Homeostasis, temperature regulation, and blood glucose control

Pilot questions 4.4

1. Define homeostasis and name two physiological variables it maintains.
2. Describe the components of a negative feedback loop.
3. Name four physiological responses that lower body temperature in humans.
4. Describe the role of insulin in blood glucose regulation.
5. Describe the role of glucagon in blood glucose regulation.

Series Summary

This Series examined the **movement of substances and the maintenance of internal balance** in living organisms. You explored the structure and functions of the cell membrane through the fluid mosaic model, the mechanisms of passive and active transport, and the principles of osmoregulation in both plants and animals, including the maintenance of water balance under different environmental conditions.

The Series then focused on excretion, transport, and homeostasis, covering the structure and function of the nephron, the composition and roles of blood and the lymphatic system, and the regulation of body temperature and blood glucose through negative feedback mechanisms. By completing this Series, you should now be able to explain membrane transport and osmoregulation, describe the processes of excretion and transport in living organisms, analyse the mechanisms of homeostatic regulation, and apply these concepts to biological systems, thereby achieving all four **Series Learning Outcomes (SLOs 4.1 to 4.4)**.

Glossary of Terms

- **Endotherm:** an organism that maintains body temperature primarily through internal metabolic heat production.
- **Glucagon:** a pancreatic hormone secreted by alpha cells that raises blood glucose through glycogenolysis and gluconeogenesis.
- **Homeostasis:** the maintenance of a stable internal physiological environment despite external changes.
- **Insulin:** a pancreatic hormone secreted by beta cells that lowers blood glucose by promoting cellular glucose uptake and glycogenesis.
- **Negative feedback:** a regulatory mechanism in which a deviation from a set point triggers a response that returns the variable toward the set point.

- **Plasmolysis:** the shrinkage of the plasma membrane away from the cell wall when a plant cell loses water to a hypertonic solution.
- **Turgor pressure:** the pressure exerted by cell contents against the rigid plant cell wall when the cell is turgid.

Concept Check Questions [Series 4]

Objective Questions

1. In the fluid mosaic model, ________ molecules interspersed among phospholipids moderate membrane fluidity. (Linked to SLO 4.1)
2. Pure water has a water potential of ________ , with solutions having negative values. (Linked to SLO 4.2)
3. Urine formation involves filtration, selective ________ , and secretion. (Linked to SLO 4.3)
4. Homeostatic regulation operates through ________ feedback loops. (Linked to SLO 4.4)
5. Glucagon is secreted by ________ cells of the islets of Langerhans. (Linked to SLO 4.4)

Short-Answer Questions

1. Distinguish between integral and peripheral membrane proteins. (Linked to SLO 4.1)
2. Define turgor pressure and explain its importance in plants. (Linked to SLO 4.2)
3. Describe the three processes of urine formation. (Linked to SLO 4.3)
4. Name the components of a negative feedback loop. (Linked to SLO 4.4)
5. Distinguish between insulin and glucagon in blood glucose regulation. (Linked to SLO 4.4)

Long-Answer Questions

1. Describe the fluid mosaic model and explain membrane transport mechanisms. (Linked to SLO 4.1)
2. Explain osmosis, water potential, and osmoregulation in animals and plants. (Linked to SLO 4.2)
3. Describe homeostasis, temperature regulation, and blood glucose control. (Linked to SLOs 4.3, 4.4)

Answers to Concept Check Questions [Series 4]

Objective Questions

1. Cholesterol.
2. Zero.
3. Reabsorption.
4. Negative.
5. Alpha.

Short-Answer Questions

1. Integral proteins are embedded within the bilayer; peripheral proteins are loosely associated with the surface and more easily removed.
2. Turgor pressure is pressure exerted by cell contents against the rigid cell wall; it maintains rigidity in non-woody plant tissues.
3. Filtration forces small molecules into the Bowman capsule; selective reabsorption returns useful substances to the blood; secretion actively moves additional wastes into the tubule.
4. Receptor (sensor), control centre, and effectors connected by negative feedback.
5. Insulin (from beta cells) lowers blood glucose by promoting uptake and glycogenesis; glucagon (from alpha cells) raises blood glucose by glycogenolysis and gluconeogenesis.

Long-Answer Questions

1. The fluid mosaic model describes a phospholipid bilayer with cholesterol and integral/peripheral proteins; hydrophilic heads face outward, hydrophobic tails inward. Transport includes passive (diffusion, facilitated diffusion, osmosis) and active (Na^+/K^+ pump, endocytosis/exocytosis) mechanisms.
2. Osmosis moves water from high to low water potential across a selectively permeable membrane. Plant cells become turgid in hypotonic solutions and plasmolysed in hypertonic solutions. Marine fish lose water by osmosis and

compensate by drinking; freshwater fish gain water and compensate with dilute urine.

3. Homeostasis maintains stable internal conditions through negative feedback (receptor, control centre, effectors). Temperature regulation uses vasodilation/sweating to cool and vasoconstriction/shivering to warm. Blood glucose is lowered by insulin (beta cells, glycogenesis) and raised by glucagon (alpha cells, glycogenolysis).

Answers to Pilot Questions [Series 4]

Part 4.1

1. The fluid mosaic model describes the membrane as a phospholipid bilayer with proteins embedded in or on it, free to move laterally, with cholesterol moderating fluidity.
2. Cholesterol moderates membrane fluidity, preventing it from becoming too rigid at low temperatures or too fluid at high temperatures.
3. Integral proteins are embedded within the bilayer; peripheral proteins are associated with the surface.
4. Transport channels, signalling receptors, and cell recognition/immune markers (or enzymes, structural links).
5. Passive transport moves substances down their gradient without energy; active transport moves substances against their gradient using ATP.

Part 4.2

1. Osmosis is the net movement of water across a selectively permeable membrane from high to low water potential; water potential measures the tendency of water to move, with pure water at zero.
2. Water leaves by osmosis, the cell contents shrink, and the plasma membrane pulls away from the cell wall in plasmolysis.

3. Turgor pressure is the pressure of cell contents against the cell wall; it keeps non-woody plant tissues rigid and drives stomatal opening.
4. Osmoregulators maintain a constant internal osmolarity regardless of the external environment; osmoconformers allow internal osmolarity to track external changes.
5. Marine fish lose water by osmosis to hypertonic seawater and compensate by drinking; freshwater fish gain water by osmosis from hypotonic surroundings and compensate by producing dilute urine.

Part 4.3

1. Excretion is the removal of metabolic waste; the main nitrogenous waste in mammals is urea.
2. Filtration (small molecules forced into Bowman capsule); selective reabsorption (useful substances returned to blood); secretion (additional wastes actively added to filtrate).
3. Plasma (transport medium), red blood cells (oxygen via haemoglobin), white blood cells (immune defence), and platelets (clotting).
4. CO_2 is transported mainly as bicarbonate ions in the plasma, and to a lesser extent as carbaminohaemoglobin in red blood cells.
5. Fluid drainage (returning interstitial fluid to the blood) and immune function (lymph nodes filter lymph and house lymphocytes).

Part 4.4

1. Homeostasis maintains stable internal conditions; examples include body temperature and blood glucose concentration.
2. A receptor detects deviation from the set point; a control centre processes this and signals effectors; effectors produce a corrective response; negative feedback returns the variable toward the set point.
3. Vasodilation, sweating, reduced metabolic heat production, and reduced activity.

4. Insulin, secreted by beta cells after a meal, promotes cellular glucose uptake, glycogenesis in the liver and muscles, and inhibits glycogen breakdown, lowering blood glucose.
5. Glucagon, secreted by alpha cells when blood glucose falls, stimulates glycogenolysis (glycogen breakdown) and gluconeogenesis in the liver, raising blood glucose back toward the set point.

References and Attributions

Textual References (Books and External Sources)

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Figures, Plates, Tables, and Boxes

- Figure 4.1: Cell membrane structure and transport Attribution: AI generated. Suggested OER search string: "fluid mosaic membrane model phospholipid bilayer membrane transport diffusion active transport diagram OER".
- Figure 4.2: Osmosis, water potential, and osmoregulation Attribution: AI generated. Suggested OER search string: "osmosis water potential turgid plasmolysis osmoregulation marine freshwater fish plant cell diagram OER".
- Figure 4.3: Excretion, blood transport, and the lymphatic system Attribution: AI generated. Suggested OER search string: "nephron urine formation kidney blood transport haemoglobin lymphatic system diagram physiology OER".
- Figure 4.4: Homeostasis, temperature regulation, and blood glucose control Attribution: AI generated. Suggested OER search string: "homeostasis negative feedback temperature regulation blood glucose insulin glucagon diagram physiology OER".

Course code: BIO 203

Course title: General Physiology

Course credit load: 2 Units

Series 5: Plant Growth and Regulation

- ## Part 5.1: Plant Water Relations
  - Sub Part 5.1.1: Water uptake and movement in plants
  - Sub Part 5.1.2: Transpiration and stomatal regulation
  - Sub Part 5.1.3: Translocation in the phloem
- ## Part 5.2: Plant Growth
  - Sub Part 5.2.1: Germination and seedling growth
  - Sub Part 5.2.2: Primary and secondary growth
  - Sub Part 5.2.3: Factors affecting plant growth
- ## Part 5.3: Plant Growth Hormones
  - Sub Part 5.3.1: Auxins
  - Sub Part 5.3.2: Gibberellins and cytokinins
  - Sub Part 5.3.3: Abscisic acid and ethylene
- ## Part 5.4: Plant Responses to the Environment
  - Sub Part 5.4.1: Phototropism and gravitropism
  - Sub Part 5.4.2: Photoperiodism and flowering
  - Sub Part 5.4.3: Plant responses to stress

Introduction

Plants are sessile organisms that cannot move away from unfavourable conditions, yet they display a remarkable capacity to sense and respond to their environment, adjust their water relations, coordinate growth across distant tissues, and regulate the timing of developmental events such as flowering and seed germination. This coordination depends on a set of chemical signalling molecules, the plant growth hormones, operating through the plant vascular system and cell signalling pathways.

This final Series of BIO 203 covers plant water relations including water uptake, transpiration, and phloem translocation; primary and secondary plant growth and the factors that affect it; the major plant growth hormones and their physiological roles; and plant environmental responses including phototropism, gravitropism, photoperiodism, and stress responses.

Series Learning Outcomes

Upon completing this Series, you should be able to:

- **SLO 5.1** describe water uptake and movement in plants, transpiration, stomatal regulation, and phloem translocation,
- **SLO 5.2** describe germination, primary and secondary growth, and the factors affecting plant growth,
- **SLO 5.3** explain the roles of auxins, gibberellins, cytokinins, abscisic acid, and ethylene in plant growth regulation, and
- **SLO 5.4** describe phototropism, gravitropism, photoperiodism, and plant stress responses.

5.1 Plant Water Relations

5.1.1 Water uptake and movement in plants

Water is absorbed from the soil by root hair cells, which have a large surface area and thin walls adapted for absorption; water enters by osmosis because the root hair cell cytoplasm has a lower water potential than the soil solution in most circumstances; once inside the root, water moves across the cortex toward the xylem through two pathways: the apoplast pathway (through the cell walls and intercellular spaces, without crossing cell membranes) and the symplast pathway (through the cytoplasm connected by plasmodesmata), before passing through the Casparian strip (an impermeable waxy band in the endodermal cell walls) which forces all water through the symplast at this point, allowing the plant to control mineral ion entry.

Water moves upward through the xylem vessels (dead, hollow, lignified cells forming a continuous tube from root to leaf) primarily driven by the cohesion-tension mechanism: transpiration from leaves (Part 5.1.2) creates tension (negative pressure) in the leaf mesophyll cells, which is transmitted via the cohesive hydrogen bonds between water molecules throughout the continuous water column in the xylem, pulling water upward from the roots; root pressure (positive pressure generated by active mineral uptake into the xylem) provides an additional, smaller upward force, most significant in young or small plants.

Fill in the blank: The Casparian strip in the endodermis forces all water through the ________ pathway, allowing the plant to control mineral ion entry into the xylem.

5.1.2 Transpiration and stomatal regulation

Transpiration is the loss of water vapour from plant surfaces, primarily through stomata (pores in the leaf epidermis surrounded by pairs of guard cells that control pore opening); approximately 90 percent of water lost from a plant is through stomatal transpiration, making stomatal regulation critical for balancing water loss against the need for CO_2 entry for photosynthesis; the rate of transpiration is affected by light (stomata open in light to allow CO_2 entry, increasing water loss), temperature (higher temperatures increase evaporation rate), humidity (lower humidity increases the water vapour gradient driving transpiration), and wind speed (increasing transpiration by removing humid air from the leaf surface).

Guard cells regulate stomatal opening by changing their turgor: when guard cells take up water by osmosis (driven by active potassium ion uptake), they swell and their thickened inner walls cause them to bow outward, opening the stoma; when guard cells lose water, they lose turgor and the stoma closes; abscisic acid (ABA) triggers stomatal closure under water stress by causing guard cells to lose potassium ions and water, a critical adaptation preventing excessive water loss under drought conditions.

Fill in the blank: Guard cells regulate stomatal opening by changing their ________ : they swell and open the stoma when they take up water, and close it when they lose water.

5.1.3 Translocation in the phloem

Translocation is the movement of dissolved organic solutes (primarily sucrose, and also amino acids and other organic molecules) from sources (where they are produced or released, mainly photosynthetically active leaves) to sinks (where they are consumed or stored, including roots, growing shoot tips, developing fruits, and seeds) through the phloem sieve tubes; phloem transport is bidirectional (unlike xylem, which transports water only upward), since different sinks may be above or below a given source leaf.

The pressure-flow hypothesis (mass flow hypothesis) explains phloem translocation: active loading of sucrose into the phloem at the source reduces water potential, causing water to enter by osmosis and generating positive pressure; at the sink, active unloading of sucrose raises water potential, causing water to leave the phloem; this creates a pressure gradient that drives mass flow of phloem sap from source to sink; phloem transport requires metabolic energy for the active loading and unloading processes, unlike the largely passive cohesion-tension mechanism driving xylem transport.

Fill in the blank: The pressure-flow hypothesis explains phloem translocation as driven by a ________ gradient created by active loading of sucrose at the source and unloading at the sink.

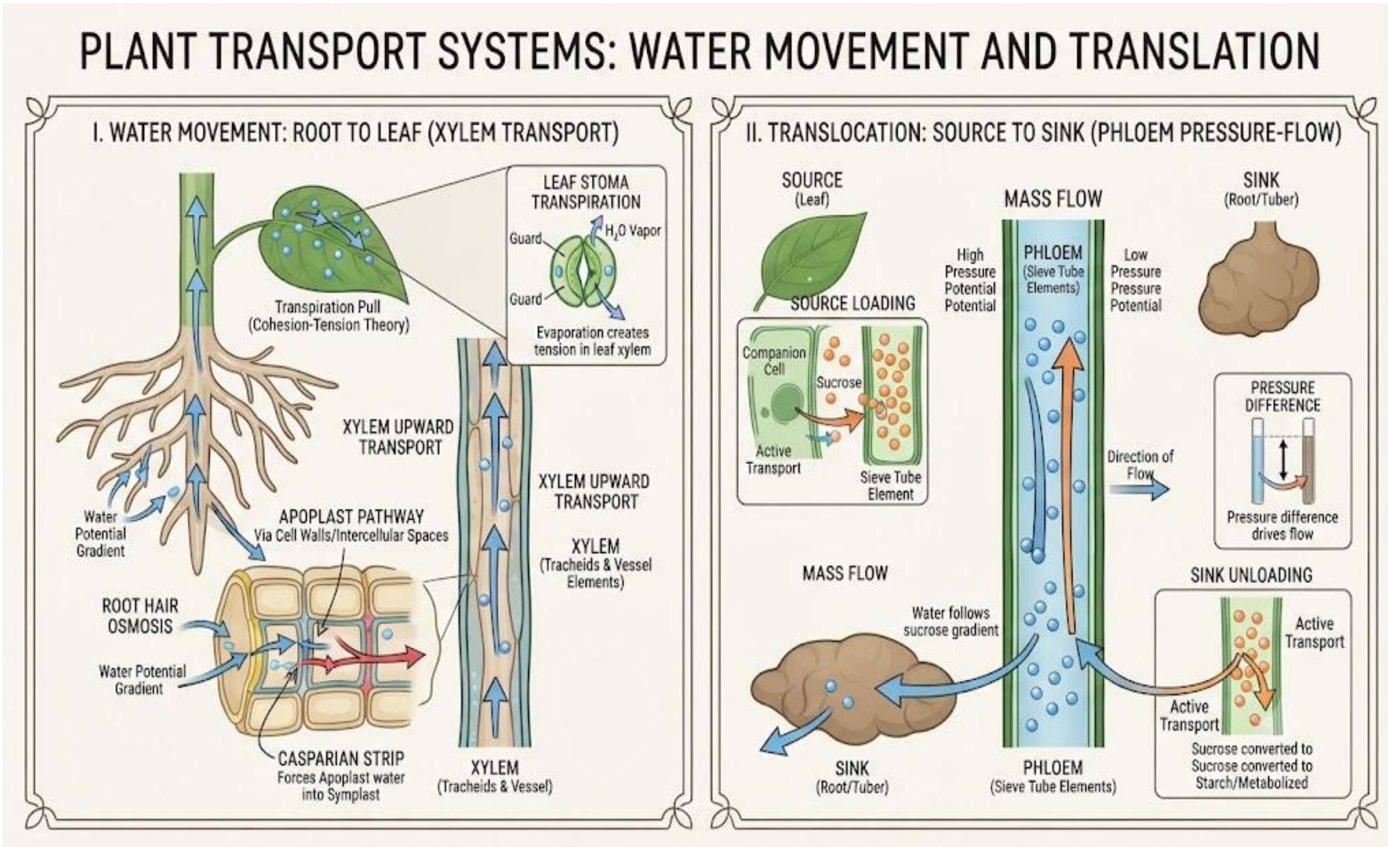

Figure 5.1: Plant water relations and translocation

Pilot questions 5.1

1. Distinguish between the apoplast and symplast pathways for water movement across the root cortex.
2. Explain the role of the Casparian strip.
3. Describe the cohesion-tension mechanism of water movement in the xylem.
4. Explain how guard cells regulate stomatal opening.
5. Describe the pressure-flow hypothesis of phloem translocation.

5.2 Plant Growth

5.2.1 Germination and seedling growth

Seed germination is the resumption of active growth from the dormant embryo within the seed, triggered when suitable conditions (adequate water, appropriate temperature, and, in some seeds, light) are met; water uptake (imbibition) activates metabolic processes within the seed, including enzyme activation (amylases, proteases, and lipases mobilising stored food reserves) and the activation of gibberellin signalling that stimulates the aleurone layer to produce alpha-amylase for starch digestion; the embryonic root (radicle) typically emerges first, followed by the shoot (plumule).

Seedling establishment depends on the food reserves stored in the seed (endosperm and/or cotyledons) until the seedling has developed sufficient leaf area for photosynthesis to supply its own energy needs; the direction of seedling growth is oriented by gravitropism (roots growing downward, shoots upward, described further in Part 5.4.1) from the earliest stages of germination, ensuring that the root system develops into the soil and the shoot system grows upward toward the light.

Fill in the blank: Water uptake (imbibition) during germination activates metabolic processes including ________ signalling that stimulates starch digestion by alpha-amylase in the aleurone layer.

5.2.2 Primary and secondary growth

Primary growth is growth in length, occurring at the apical meristems (regions of actively dividing undifferentiated cells) at the tips of roots and shoots; cells produced by the apical meristem divide, elongate (driven largely by cell turgor and auxin-stimulated cell wall loosening), and differentiate into the various tissue types of the root or shoot (epidermis, cortex, vascular bundles); primary growth occurs throughout the growing season in all vascular plants.

Secondary growth is growth in girth (thickness), occurring in many dicotyledonous plants and gymnosperms through the activity of the vascular cambium (a lateral meristem producing secondary xylem/wood toward the inside and secondary phloem toward the outside) and the cork cambium (a lateral meristem producing cork, forming the outer protective bark layer); secondary growth is responsible for the thickening of tree trunks and woody stems, and the annual rings visible in a tree cross-section represent seasonal variations in the size of secondary xylem cells produced during different parts of the growing season.

Fill in the blank: Secondary growth in girth occurs through the activity of the vascular ________ , which produces secondary xylem toward the inside and secondary phloem toward the outside.

5.2.3 Factors affecting plant growth

Internal factors affecting plant growth include the genetic programme of the plant (determining its growth form, maximum size, and developmental timing), the availability of growth hormones (Part 5.3), and the nutritional status of the plant (adequate supply of water, minerals, and photosynthate being required for active growth); plants that are deficient in essential nutrients or water show characteristic growth defects and reduced biomass accumulation.

External (environmental) factors affecting plant growth include light (intensity and quality driving photosynthesis; photoperiod affecting flowering and dormancy, Part 5.4.2), temperature (affecting enzymatic reaction rates and development, with most temperate plants having a temperature range within which growth occurs and outside which it stops), water availability (both deficit and excess being limiting), and soil nutrient availability; these external factors interact with internal hormone signalling to produce the integrated growth response the plant displays.

Fill in the blank: External factors affecting plant growth include light, temperature, water availability, and soil ________ availability, interacting with internal hormone signalling.

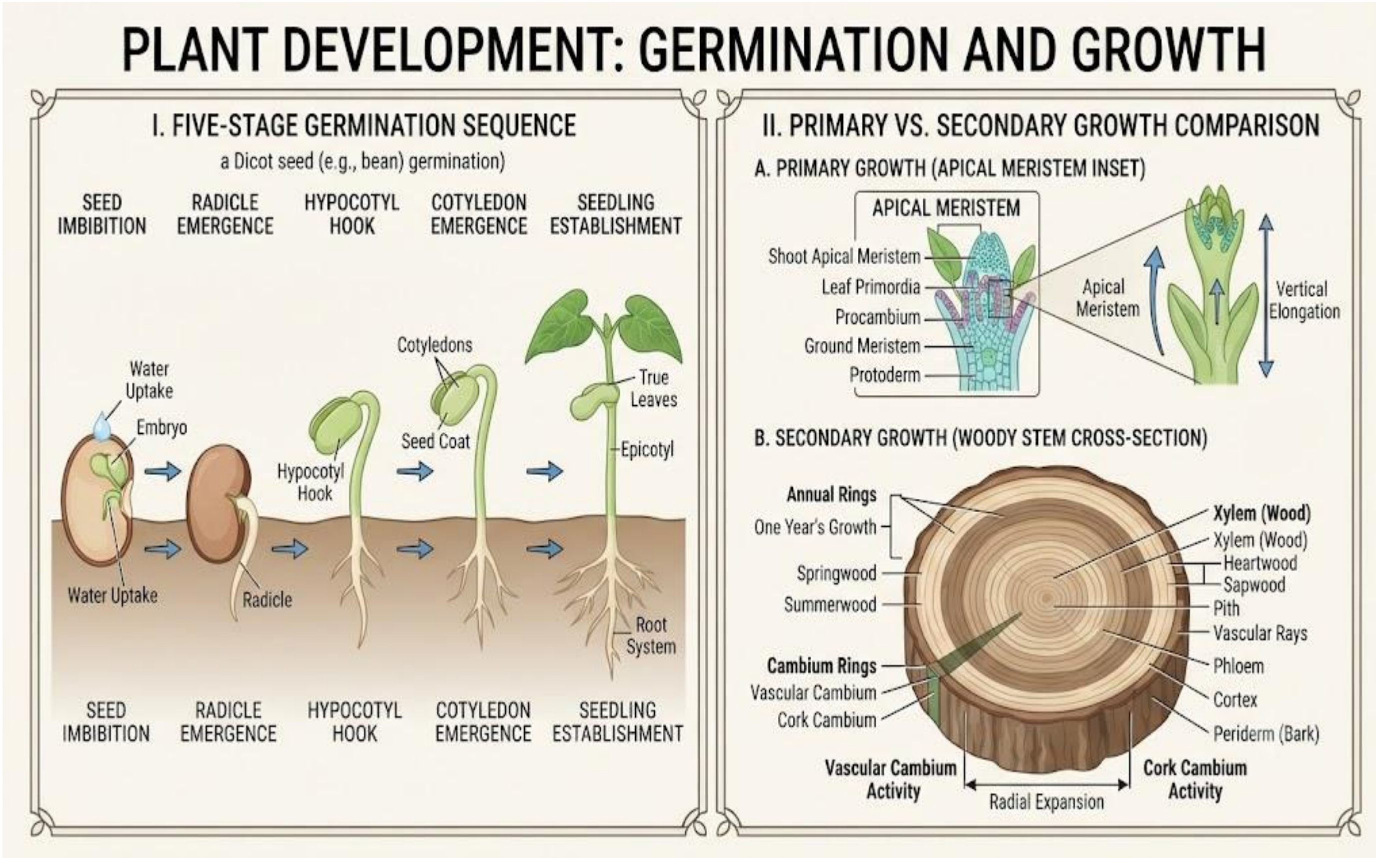

Figure 5.2: Plant growth, germination, and meristems

Pilot questions 5.2

1. Describe the sequence of events in seed germination.
2. Explain the role of gibberellins in germination.
3. Distinguish between primary and secondary growth.
4. Define apical meristem and vascular cambium.
5. Name three external factors affecting plant growth.

5.3 Plant Growth Hormones

5.3.1 Auxins

Auxins (principally indole-3-acetic acid, IAA) are produced primarily in the shoot apical meristem and young leaves, and transported downward through the plant in a polar, directional manner; their primary effect at low to moderate concentrations is to promote cell elongation by stimulating the loosening of cell wall bonds (allowing cells to expand as they take up water), thus driving the elongation phase of primary growth; at higher concentrations auxin inhibits rather than promotes growth in some tissues, creating a complex dose-response relationship.

Auxins mediate apical dominance (the suppression of lateral bud growth by the apical shoot tip, due to high auxin concentration from the tip inhibiting lateral bud growth; removal of the apical tip allows lateral buds to grow, a principle exploited in pruning to promote bushy growth) and phototropism (unequal auxin distribution causing differential elongation between the shaded and illuminated sides of a shoot, described further in Part 5.4); auxins are also used commercially in promoting rooting of cuttings and preventing premature fruit drop.

Fill in the blank: Apical dominance is the suppression of lateral bud growth by high ________ concentration from the shoot tip, released by removing the tip through pruning.

5.3.2 Gibberellins and cytokinins

Gibberellins (GAs, a family of related compounds, with gibberellin A3/GA3 being a well-studied example) stimulate stem elongation (through both cell division and cell elongation), seed germination (stimulating alpha-amylase production in the aleurone layer to mobilise seed food reserves), and the transition from vegetative growth to flowering in some plants; treatment of dwarf plant varieties with gibberellins can restore normal stem elongation, demonstrating that the dwarfism of these varieties is due to gibberellin deficiency or signalling defects.

Cytokinins (plant hormones promoting cell division, named for their role in cytokinesis) are synthesised primarily in actively dividing tissues and in the roots; they promote cell division in the presence of auxin (the ratio of cytokinin to auxin in tissue culture determines whether cells form shoots or roots, a discovery with major importance for plant biotechnology), delay leaf senescence (ageing and yellowing), and counteract apical dominance by promoting lateral bud growth, acting antagonistically to auxin at this point.

Fill in the blank: Cytokinins are named for their role in ________ , promoting cell division; they counteract apical dominance and delay leaf senescence.

5.3.3 Abscisic acid and ethylene

Abscisic acid (ABA) is often described as a stress hormone because its levels rise in response to water deficit (drought), cold temperatures, and other stresses; its primary role in water stress response is to trigger stomatal closure (by causing guard cells to lose potassium ions and water, reducing turgor and closing the stoma), reducing water loss under drought conditions; ABA also promotes seed dormancy and inhibits germination until favourable conditions arrive, making it an important regulator of seasonal dormancy and timing of germination.

Ethylene is unique among plant hormones in being a gas (C2H4) at physiological temperatures, allowing it to diffuse through tissues and act as a local and short-range signal; it promotes fruit ripening (stimulating the enzymatic processes softening fruit tissue and converting starch to sugars, and triggering pigment changes such as chlorophyll breakdown and carotenoid/anthocyanin formation), promotes leaf and fruit abscission (the seasonal shedding of leaves and fruit from the plant), inhibits stem elongation, and is involved in responses to mechanical stress (touch-induced thickening of stems in plants subjected to wind or physical contact).

Fill in the blank: Ethylene is unique among plant hormones in being a ________ at physiological temperatures, allowing it to diffuse through tissues as a local signal.

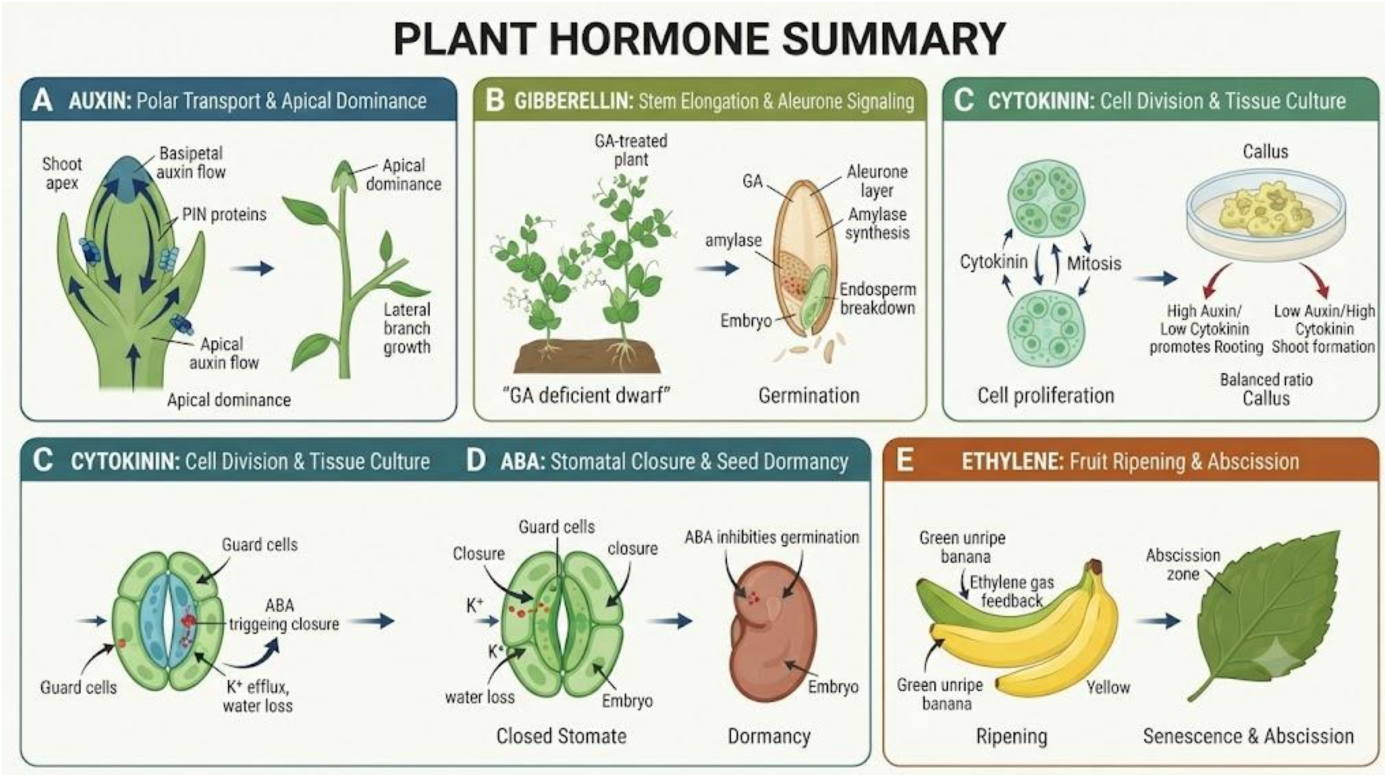

Figure 5.3: Plant growth hormones and their roles

Pilot questions 5.3

1. Describe two physiological effects of auxins.
2. Explain the role of gibberellins in seed germination.
3. Explain the antagonistic relationship between auxins and cytokinins in apical dominance.
4. Describe the role of abscisic acid in plant water stress response.
5. Name three effects of ethylene on plant physiology.

5.4 Plant Responses to the Environment

5.4.1 Phototropism and gravitropism

Phototropism is the directional growth response of a plant organ toward (positive phototropism) or away from (negative phototropism) a light source; shoots display positive phototropism (growing toward light) and roots typically display negative phototropism; the mechanism involves unequal distribution of auxin in response to unidirectional light, with auxin migrating to the shaded side of the shoot and stimulating greater cell elongation on that side, causing the shoot to bend toward the light.

Gravitropism (geotropism) is the directional growth response to gravity; roots display positive gravitropism (growing downward in the direction of gravity) and shoots display negative gravitropism (growing upward, against gravity); the perception of gravity involves specialised cells (statocytes) containing dense starch granules (statoliths) that settle under gravity and are thought to trigger signalling that results in asymmetric auxin distribution and differential elongation, causing the root or shoot to curve in the appropriate direction.

Fill in the blank: Phototropism in shoots is mediated by ________ migrating to the shaded side, stimulating greater elongation on that side and causing the shoot to bend toward light.

5.4.2 Photoperiodism and flowering

Photoperiodism is the ability of a plant to detect and respond to the relative length of day and night (photoperiod), controlling developmental processes such as flowering, seed dormancy, and leaf senescence; plants are classified by their flowering response to photoperiod: long-day plants (actually short-night plants) flower when the night length falls below a critical minimum, typically in summer (examples include wheat, barley, and many temperate wildflowers); short-day plants (actually long-night plants) flower when the night length exceeds a critical minimum, typically in autumn (examples include chrysanthemum and soybean); and day-neutral plants flower independently of photoperiod.

The photoreceptor responsible for photoperiodism is phytochrome, a pigment that exists in two interconvertible forms: Pr (phytochrome red, absorbing red light and converting to Pfr) and Pfr (phytochrome far-red, absorbing far-red light and converting back to Pr; Pfr also slowly reverts to Pr in darkness); the ratio of Pr to Pfr changes with the photoperiod and light quality, and it is thought that the Pfr form is the active signalling form that influences flowering and other developmental responses, with plants using changes in this ratio to track seasonal changes in day length.

Fill in the blank: The photoreceptor responsible for photoperiodism is ________ , a pigment that exists in two interconvertible forms: Pr (absorbs red light) and Pfr (absorbs far-red light).

5.4.3 Plant responses to stress

Plants face a range of abiotic stresses (water deficit, flooding, temperature extremes, high salinity, and high light intensity) and biotic stresses (herbivory, pathogen attack) to which they have evolved diverse physiological and biochemical responses; drought stress triggers ABA signalling leading to stomatal closure and altered gene expression, root growth toward water, and the accumulation of compatible solutes (small organic molecules such as proline and glycine betaine that maintain cell turgor without toxicity) to maintain osmotic balance at lower water potentials.

Pathogen attack triggers the hypersensitive response (localised cell death at the infection site, limiting pathogen spread), the production of antimicrobial compounds (phytoalexins), and systemic acquired resistance (SAR), in which signalling molecules including salicylic acid spread from the infection site to prime resistance throughout the plant; physical stresses such as mechanical wounding trigger rapid responses including protease inhibitor production (reducing digestibility for herbivores) mediated by the hormone jasmonic acid, illustrating the breadth and sophistication of plant immune and stress responses.

Fill in the blank: Systemic acquired ________ (SAR) is a plant defence mechanism in which signals from a pathogen infection site prime resistance throughout the entire plant.

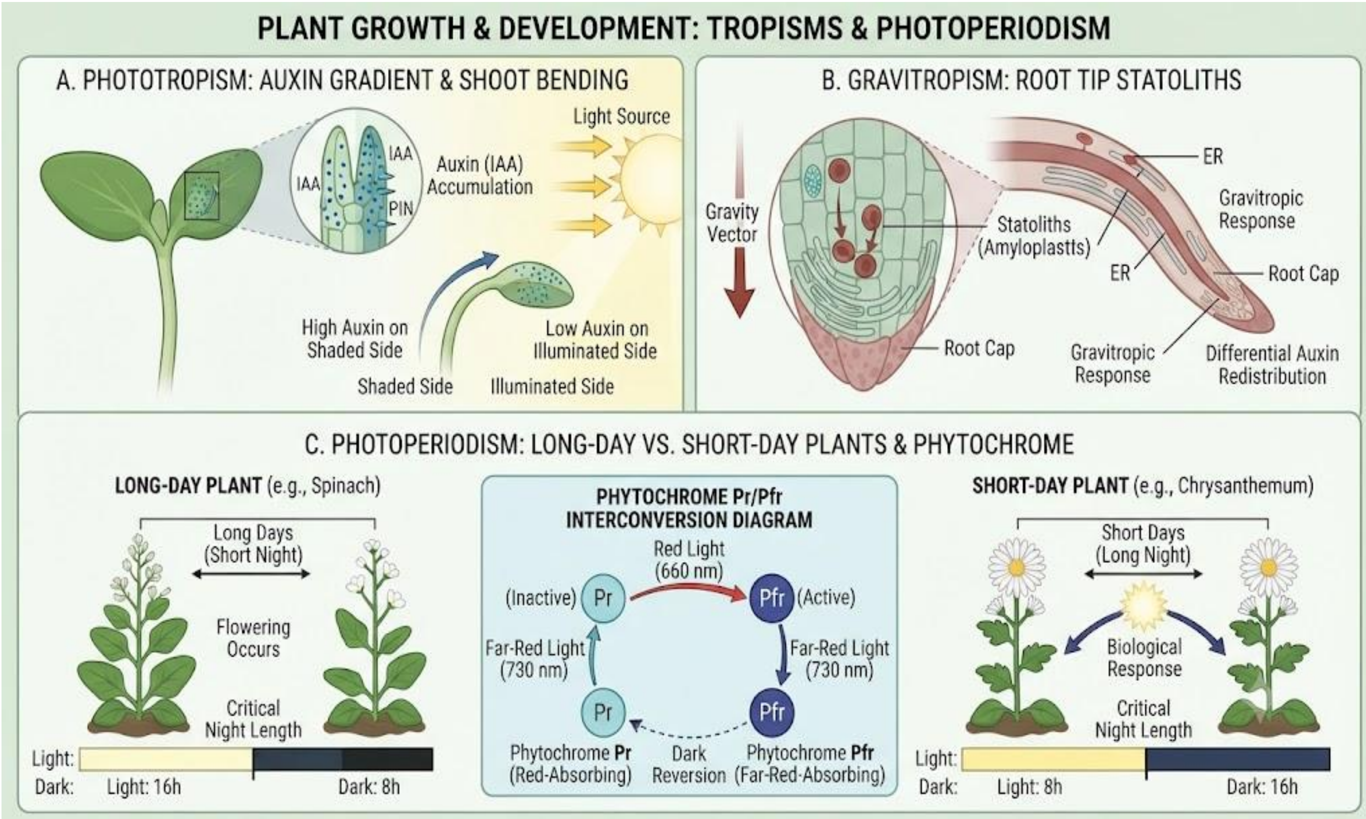

Figure 5.4: Plant environmental responses

Pilot questions 5.4

1. Describe the mechanism of shoot phototropism.
2. Distinguish between positive and negative gravitropism in roots and shoots.
3. Distinguish between long-day and short-day plants in their flowering response.
4. Describe the two interconvertible forms of phytochrome.
5. Name two plant responses to pathogen attack.

Series Summary

This Series explored the **physiological processes that enable plant growth, transport, and environmental adaptation**. You examined plant water relations, including water uptake by roots, transport through the xylem and phloem, transpiration, stomatal regulation, and the factors influencing plant growth, from seed germination to primary and secondary growth.

Building on these concepts, the Series explained the roles of major plant hormones in regulating growth and development, as well as plant responses to environmental stimuli such as light, gravity, day length, drought, and pathogen or herbivore attack. By completing this Series, you should now be able to explain water transport and growth processes in plants, describe the functions of key plant hormones, analyse plant responses to environmental factors, and apply these concepts to plant physiology, thereby achieving all four **Series Learning Outcomes (SLOs)** and the **overall course outcomes**.

Glossary of Terms

- **Apical dominance:** the suppression of lateral bud growth by high auxin concentration from the shoot apical meristem.
- **Casparian strip:** an impermeable waxy band in the endodermis that forces water into the symplast pathway, allowing control of mineral entry.
- **Cohesion-tension mechanism:** the driving force for xylem water movement, using transpiration-generated tension transmitted through cohesive water columns.
- **Phytochrome:** a plant photoreceptor pigment existing in Pr and Pfr forms, responsible for photoperiodism and other light-regulated responses.
- **Pressure-flow hypothesis:** the explanation for phloem translocation, driven by a pressure gradient between high-pressure source and low-pressure sink.
- **Systemic acquired resistance (SAR):** a plant-wide defence state primed by pathogen infection at one site, mediated by salicylic acid signalling.

- **Transpiration:** the loss of water vapour from plant surfaces, primarily through stomata.

Concept Check Questions [Series 5]

Objective Questions

1. The Casparian strip forces water into the ________ pathway at the endodermis. (Linked to SLO 5.1)
2. Secondary growth in girth occurs through the activity of the vascular ________ . (Linked to SLO 5.2)
3. Apical dominance is the suppression of lateral buds by high ________ concentration from the shoot tip. (Linked to SLO 5.3)
4. The plant photoreceptor responsible for photoperiodism is ________ . (Linked to SLO 5.4)
5. Ethylene is unique among plant hormones in being a ________ at physiological temperatures. (Linked to SLO 5.3)

Short-Answer Questions

1. Describe the cohesion-tension mechanism of xylem transport. (Linked to SLO 5.1)
2. Distinguish between primary and secondary growth. (Linked to SLO 5.2)
3. Name two effects of auxins. (Linked to SLO 5.3)
4. Distinguish between long-day and short-day plants. (Linked to SLO 5.4)
5. Name two plant responses to drought stress. (Linked to SLO 5.4)

Long-Answer Questions

1. Describe water movement in plants, transpiration, and phloem translocation. (Linked to SLO 5.1)
2. Describe plant growth and the roles of auxins, gibberellins, cytokinins, ABA, and ethylene. (Linked to SLOs 5.2, 5.3)

3. Explain phototropism, gravitropism, photoperiodism, and plant stress responses. (Linked to SLO 5.4)

Answers to Concept Check Questions [Series 5]

Objective Questions

1. Symplast.
2. Cambium.
3. Auxin.
4. Phytochrome.
5. Gas.

Short-Answer Questions

1. Transpiration from leaves creates tension transmitted via cohesive water molecules throughout the xylem column, pulling water upward from the roots.
2. Primary growth increases length at apical meristems; secondary growth increases girth through lateral meristems (vascular cambium, cork cambium).
3. Cell elongation promotion and apical dominance (or phototropism mediation, rooting of cuttings).
4. Long-day plants flower when night length falls below a critical minimum; short-day plants flower when night length exceeds a critical minimum.
5. ABA-triggered stomatal closure and accumulation of compatible solutes to maintain turgor.

Long-Answer Questions

1. Water enters root hairs by osmosis, travels the cortex via apoplast and symplast pathways, passes through the Casparian strip into the xylem, and moves upward by cohesion-tension driven by transpiration. Stomata are regulated by guard cell turgor, with ABA causing closure under stress. Phloem transports sucrose from source to sink by pressure-flow driven by active loading and unloading.

2. Germination involves imbibition, gibberellin signalling for alpha-amylase, then radicle and plumule emergence. Primary growth at apical meristems elongates roots and shoots; secondary growth via vascular/cork cambium increases girth. Auxin promotes elongation and apical dominance; gibberellins stimulate elongation and germination; cytokinins promote division; ABA closes stomata and promotes dormancy; ethylene ripens fruit and causes abscission.
3. Phototropism is caused by auxin migrating to the shaded side of shoots, promoting unequal elongation and bending toward light. Gravitropism uses statoliths to detect gravity, directing root growth downward and shoot growth upward. Photoperiodism uses phytochrome (Pr/Pfr) to detect critical night length, controlling flowering in long-day and short-day plants. Drought triggers ABA signalling; pathogen attack induces SAR via salicylic acid; wounding induces jasmonic acid signalling.

Answers to Pilot Questions [Series 5]

Part 5.1

1. Apoplast pathway goes through cell walls without crossing membranes; symplast pathway goes through connected cytoplasm via plasmodesmata.
2. The Casparian strip forces all water through the symplast at the endodermis, allowing the plant to control which mineral ions enter the xylem.
3. Transpiration from leaves creates tension in mesophyll cells, transmitted via cohesive water molecules throughout the xylem, pulling the water column upward from the roots.
4. Guard cells take up K+ ions actively, lowering water potential; water enters by osmosis, increasing turgor; the thickened inner walls bow outward, opening the stoma.
5. Active sucrose loading at the source reduces water potential, drawing in water and raising pressure; active unloading at the sink raises water potential; the pressure gradient drives mass flow from source to sink.

Part 5.2

1. Imbibition, enzyme activation, gibberellin signalling for alpha-amylase production, mobilisation of food reserves, radicle emergence, then plumule emergence.
2. Gibberellins stimulate the aleurone layer to produce alpha-amylase, which digests starch to provide energy for the growing embryo.
3. Primary growth increases length at apical meristems; secondary growth increases girth through the vascular cambium and cork cambium.
4. Apical meristem: actively dividing region at root and shoot tips driving primary growth. Vascular cambium: lateral meristem producing secondary xylem and phloem.
5. Light, temperature, and water availability (or soil nutrient availability).

Part 5.3

1. Cell elongation promotion (cell wall loosening) and mediation of apical dominance.
2. Gibberellins stimulate the aleurone layer to produce alpha-amylase, mobilising stored food reserves from the endosperm for the growing embryo.
3. Auxin from the shoot tip suppresses lateral bud growth; cytokinins counteract this by promoting lateral bud growth; removing the tip releases the lateral buds from suppression.
4. ABA triggers guard cells to lose K^+ ions and water, reducing turgor and closing stomata, reducing water loss under drought.
5. Fruit ripening, leaf and fruit abscission, and inhibition of stem elongation (or touch-induced stem thickening).

Part 5.4

1. Unidirectional light causes auxin to migrate to the shaded side; greater elongation on that side causes the shoot to bend toward the light source.
2. Roots show positive gravitropism (grow toward gravity, downward); shoots show negative gravitropism (grow against gravity, upward).

3. Long-day plants flower when night length falls below a critical minimum (flower in long days/short nights); short-day plants flower when night length exceeds a critical minimum (flower in short days/long nights).
4. Pr absorbs red light and converts to Pfr; Pfr absorbs far-red light and converts back to Pr; Pfr also slowly reverts to Pr in darkness.
5. Hypersensitive response (localised cell death at infection site) and systemic acquired resistance (SAR) spreading pathogen resistance throughout the plant via salicylic acid signalling.

References and Attributions

Textual References (Books and External Sources)

- Campbell, N. A., & Reece, J. B. (2018). Biology (11th ed.). Pearson.
- Taiz, L., Zeiger, E., Moller, I. M., & Murphy, A. (2015). Plant physiology and development (6th ed.). Sinauer Associates.
- Guyton, A. C., & Hall, J. E. (2015). Textbook of medical physiology (13th ed.). Elsevier.
- National Open University of Nigeria (NOUN). (2023). General physiology course material. NOUN Press.

Figures, Plates, Tables, and Boxes

- Figure 5.1: Plant water relations and translocation Attribution: AI generated. Suggested OER search string: "plant water uptake xylem transpiration stomata guard cells phloem translocation pressure flow diagram OER".
- Figure 5.2: Plant growth, germination, and meristems Attribution: AI generated. Suggested OER search string: "plant germination seedling primary secondary growth apical meristem vascular cambium annual ring diagram OER".
- Figure 5.3: Plant growth hormones and their roles Attribution: AI generated. Suggested OER search string: "plant hormones auxin gibberellin cytokinin abscisic acid ethylene functions diagram physiology OER".
- Figure 5.4: Plant environmental responses Attribution: AI generated. Suggested OER search string: "phototropism gravitropism auxin photoperiodism phytochrome long day short day plant flowering diagram OER".