Chapter 12: Respiration in Plants

Exercises — Exercises

Q1 Differentiate between (a) Respiration and Combustion (b) Glycolysis and Krebs' cycle (c) Aerobic respiration and Fermentation

SOLUTION

(a) Respiration vs Combustion:

Respiration: A biological process occurring in living cells. Glucose is oxidised in a series of enzyme-controlled, stepwise reactions. Energy is released gradually and a significant portion is trapped as ATP (chemical energy). It occurs at body/room temperature. CO_2, H_2O and ATP are produced.

Combustion: A physical/chemical process. Glucose is oxidised rapidly in a single, uncontrolled step. All energy is released at once as heat and light. It occurs at high temperatures. No ATP is formed; only CO_2 and H_2O are produced.

(b) Glycolysis vs Krebs' cycle:

Glycolysis: Occurs in the cytoplasm. Does not require oxygen (common to both aerobic and anaerobic respiration). One glucose (6C) is split into two pyruvate (3C) molecules. Net gain = 2 ATP and 2 NADH per glucose. No CO_2 is released.

Krebs' cycle (TCA cycle): Occurs in the mitochondrial matrix. Requires aerobic conditions (indirectly). Acetyl CoA (2C) condenses with OAA (4C) to form citrate (6C); the cycle turns twice per glucose. Per glucose: 2 ATP (via GTP), 6 NADH, 2 $FADH_2$, and 4 CO_2 are produced.

(c) Aerobic respiration vs Fermentation:

Aerobic respiration: Occurs in the presence of O_2. Glucose is completely oxidised to CO_2 and H_2O. Pyruvate enters mitochondria and is fully oxidised via Krebs' cycle and ETS. Large energy yield — net 38 ATP per glucose. Occurs in most eukaryotes under normal conditions.

Fermentation: Occurs in the absence of O_2 (anaerobic). Glucose is incompletely oxidised. Pyruvate is converted to either ethanol + CO_2 (alcoholic fermentation) or lactic acid (lactic acid fermentation). Only 2 net ATP are produced per glucose. NADH is reoxidised to NAD^+ to allow glycolysis to continue. Occurs in yeast, some bacteria, and muscle cells under oxygen deficit.

Answer: (a) Respiration is enzymatic, stepwise, energy-trapped as ATP; combustion is rapid, uncontrolled, energy lost as heat. (b) Glycolysis occurs in cytoplasm, splits glucose to pyruvate (2 ATP); Krebs' cycle occurs in mitochondrial matrix, oxidises acetyl CoA completely (2 ATP + 6 NADH + 2 FADH2 per glucose). (c) Aerobic respiration completely oxidises glucose to CO2 + H2O yielding 38 ATP; fermentation incompletely oxidises glucose anaerobically to ethanol or lactic acid yielding only 2 ATP.

Q2 What are respiratory substrates? Name the most common respiratory substrate.

SOLUTION

Respiratory substrates are the organic compounds that are oxidised during the process of cellular respiration to release energy in the form of ATP.

These compounds include carbohydrates (glucose, starch, sucrose), fats (fatty acids and glycerol), proteins (amino acids after deamination), and organic acids. Each substrate enters the respiratory pathway at a different point — fats enter as acetyl CoA, proteins enter as pyruvate, acetyl CoA, or intermediates of the Krebs' cycle, depending on the amino acid.

The most common (favoured) respiratory substrate is glucose (a hexose sugar). All other carbohydrates are first converted to glucose before being used for respiration.

Answer: Respiratory substrates are organic compounds oxidised during cellular respiration to yield energy. Glucose is the most common respiratory substrate.

Q3 Give the schematic representation of glycolysis?

SOLUTION

Glycolysis (EMP pathway) — occurs in the cytoplasm:

Glucose (6C)
| ATP --> ADP [hexokinase]
Glucose-6-phosphate (6C)
| [phosphoglucoisomerase]
Fructose-6-phosphate (6C)
| ATP --> ADP [phosphofructokinase]
Fructose-1,6-bisphosphate (6C)

	[aldolase]

+-- Dihydroxyacetone phosphate (DHAP, 3C) <-- [isomerase] -->
+-- Glyceraldehyde-3-phosphate (PGAL, 3C)
| NAD+ --> NADH+H+ (x2)
2 x 1,3-bisphosphoglyceric acid (BPGA, 3C)
| ADP --> ATP (x2) [substrate-level phosphorylation]
2 x 3-phosphoglyceric acid (PGA, 3C)
|
2 x 2-phosphoglycerate (3C)
| H2O removed
2 x Phosphoenolpyruvate (PEP, 3C)
| ADP --> ATP (x2) [substrate-level phosphorylation]
2 x Pyruvic acid (3C)

Net balance per glucose:
ATP used: 2 (at glucose --> G6P and F6P --> F1,6-BP)
ATP gained: 4 (2 from BPGA --> PGA + 2 from PEP --> pyruvate)
Net ATP = 2
NADH+H+ produced = 2

Answer: Glucose (6C) --> [2 ATP used] --> Fructose-1,6-bisphosphate --> 2 x PGAL (3C) --> [2 NADH, 2 ATP] --> 2 x PGA --> 2 x PEP --> [2 ATP] --> 2 x Pyruvate. Net gain: 2 ATP, 2 NADH.

Q4 What are the main steps in aerobic respiration? Where does it take place?

SOLUTION

Aerobic respiration consists of the following main steps:

1. Glycolysis (cytoplasm): Glucose (6C) is broken down into two molecules of pyruvate (3C). Net yield: 2 ATP, 2 NADH.

2. Oxidative decarboxylation of pyruvate (mitochondrial matrix): Pyruvate is converted to Acetyl CoA by pyruvate dehydrogenase complex. CO2 is released and NADH is produced. Reaction: Pyruvate + CoA + NAD+ --> Acetyl CoA + CO2 + NADH + H+

3. Krebs' cycle / TCA cycle (mitochondrial matrix): Acetyl CoA (2C) condenses

with OAA (4C) to form citrate (6C). Through a series of reactions, CO_2 is released, and NADH, $FADH_2$, and GTP (converted to ATP) are produced. Per glucose: 2 ATP (via 2 GTP), 6 NADH, 2 $FADH_2$, 4 CO_2.

4. Electron Transport System (ETS) and Oxidative Phosphorylation (inner mitochondrial membrane): NADH and $FADH_2$ donate electrons to the ETS. Electrons pass through complexes I, II, III, and IV, generating a proton gradient across the inner membrane. ATP is synthesised by ATP synthase (complex V) using this gradient (chemiosmosis). O_2 is the final electron acceptor, forming H_2O. Each NADH yields 3 ATP; each $FADH_2$ yields 2 ATP.

Location summary:
- Glycolysis: cytoplasm
- Pyruvate oxidation, Krebs' cycle: mitochondrial matrix
- ETS and oxidative phosphorylation: inner mitochondrial membrane

Answer: Main steps: (1) Glycolysis in cytoplasm, (2) Oxidative decarboxylation of pyruvate in mitochondrial matrix, (3) Krebs' cycle in mitochondrial matrix, (4) ETS and oxidative phosphorylation on inner mitochondrial membrane. O_2 is consumed only at the final step (as terminal electron acceptor).

Q5 Give the schematic representation of an overall view of Krebs' cycle.

SOLUTION

Krebs' cycle (TCA cycle) — occurs in mitochondrial matrix. One turn per acetyl CoA (cycle turns twice per glucose):

Acetyl CoA (2C) + Oxaloacetic acid (OAA, 4C) + H_2O
| [citrate synthase] --> CoA released
Citric acid (6C)
| [aconitase]
Isocitric acid (6C)
| NAD+ --> NADH+H+ ; CO_2 released [isocitrate dehydrogenase]
alpha-Ketoglutaric acid (5C)
| NAD+ --> NADH+H+ ; CO_2 released ; CoA added [alpha-ketoglutarate dehydrogenase]
Succinyl CoA (4C)
| GDP + Pi --> GTP (= ATP) ; CoA released [succinyl CoA synthetase]
Succinic acid (4C)

| FAD+ --> FADH2 [succinate dehydrogenase]
Fumaric acid (4C)
| H2O added [fumarase]
Malic acid (4C)
| NAD+ --> NADH+H+ [malate dehydrogenase]
Oxaloacetic acid (OAA, 4C) <-- cycle continues

Products per turn (per acetyl CoA):
3 NADH+H+, 1 FADH2, 1 ATP (via GTP), 2 CO2

Products per glucose (2 turns):
6 NADH+H+, 2 FADH2, 2 ATP, 4 CO2

Answer: Acetyl CoA (2C) + OAA (4C) --> Citrate (6C) --> Isocitrate --> alpha-Ketoglutarate (5C, -CO2, -NADH) --> Succinyl CoA (4C, -CO2, -NADH) --> Succinate (-ATP via GTP) --> Fumarate (-FADH2) --> Malate --> OAA (-NADH). Per glucose: 2 ATP, 6 NADH, 2 FADH2, 4 CO2.

Q6 Explain ETS.

SOLUTION

Electron Transport System (ETS):
ETS is a series of electron carriers located on the inner mitochondrial membrane. It oxidises the NADH and FADH2 produced during glycolysis, pyruvate oxidation, and the Krebs' cycle, and couples this oxidation to ATP synthesis.

Components and sequence:
1. Complex I (NADH dehydrogenase): Accepts electrons from NADH (produced in mitochondrial matrix). Transfers electrons to ubiquinone (UQ / coenzyme Q) embedded in the inner membrane.
2. Complex II (succinate dehydrogenase): Accepts electrons from FADH2 (produced during oxidation of succinate in Krebs' cycle). Also transfers electrons to ubiquinone. FADH2 enters here, so fewer protons are pumped and only 2 ATP are produced (vs 3 for NADH).
3. Ubiquinone (Coenzyme Q): Mobile electron carrier within the inner membrane. Receives electrons from both complex I and II; passes them to complex III.
4. Complex III (cytochrome bc1 complex): Transfers electrons from reduced ubiquinol to cytochrome c.
5. Cytochrome c: Small mobile protein on the outer surface of the inner

membrane. Shuttles electrons from complex III to complex IV.
6. Complex IV (cytochrome c oxidase; contains cytochromes a and a3 and two copper centres): Transfers electrons to molecular O2, the final electron acceptor. O2 is reduced to H2O.

ATP synthesis (Oxidative Phosphorylation):
As electrons move through the chain (complexes I, III, IV), protons (H+) are pumped from the mitochondrial matrix to the intermembrane space, creating an electrochemical proton gradient. This gradient drives protons back through ATP synthase (Complex V, which has F0 and F1 subunits). The flow of 4H+ through F0 powers the synthesis of 1 ATP from ADP + Pi at the F1 headpiece. This process is called oxidative phosphorylation (or chemiosmosis).

Energy yield:
Each NADH --> 3 ATP
Each FADH2 --> 2 ATP
O2 acts as the final hydrogen/electron acceptor, and its presence keeps the entire chain running.

Answer: ETS is located on the inner mitochondrial membrane. Electrons from NADH and FADH2 pass through complexes I-IV (via ubiquinone and cytochrome c) to O2 (final acceptor), forming H2O. This electron flow pumps H+ into the intermembrane space; the resulting gradient drives ATP synthesis via ATP synthase (complex V) — oxidative phosphorylation. NADH yields 3 ATP; FADH2 yields 2 ATP.

Q7 Distinguish between the following: (a) Aerobic respiration and Anaerobic respiration (b) Glycolysis and Fermentation (c) Glycolysis and Citric acid Cycle

SOLUTION

(a) Aerobic respiration vs Anaerobic respiration:
Aerobic respiration requires O2; anaerobic does not.
In aerobic respiration, glucose is completely oxidised to CO2 and H2O; in anaerobic respiration, glucose is incompletely oxidised to pyruvate, which is then converted to ethanol + CO2 or lactic acid.
Aerobic respiration yields approximately 38 ATP per glucose; anaerobic yields only 2 net ATP.
Aerobic respiration involves glycolysis + Krebs' cycle + ETS; anaerobic involves only glycolysis + fermentation reactions.

Site: aerobic uses cytoplasm + mitochondria; anaerobic uses only the cytoplasm.
Aerobic occurs in most higher organisms; anaerobic occurs in yeast, some bacteria, and in animal muscle under low-oxygen conditions.

(b) Glycolysis vs Fermentation:
Glycolysis is the partial oxidation of glucose to pyruvate; it occurs in the cytoplasm and is common to both aerobic and anaerobic pathways. It produces 2 net ATP and 2 NADH per glucose.
Fermentation is the set of reactions that follow glycolysis under anaerobic conditions. Pyruvate is converted to ethanol + CO_2 (by pyruvate decarboxylase and alcohol dehydrogenase) or to lactic acid (by lactate dehydrogenase). No additional ATP is produced in fermentation itself — its role is to regenerate NAD^+ so glycolysis can continue.
Glycolysis is universal; fermentation is specific to anaerobic organisms or conditions.

(c) Glycolysis vs Citric acid Cycle (Krebs' cycle):
Glycolysis occurs in the cytoplasm; Krebs' cycle occurs in the mitochondrial matrix.
Glycolysis does not require O_2 and is common to aerobic and anaerobic respiration; Krebs' cycle is part of aerobic respiration only.
Glycolysis converts one glucose (6C) to two pyruvate (3C); Krebs' cycle oxidises Acetyl CoA (2C) entering from pyruvate.
Glycolysis produces 2 ATP, 2 NADH, no CO_2; Krebs' cycle produces 2 ATP (via GTP), 6 NADH, 2 $FADH_2$, and 4 CO_2 per glucose.
Glycolysis is a linear pathway; Krebs' cycle is a cyclic pathway.
In glycolysis, NAD^+ is the only electron acceptor; in Krebs' cycle both NAD^+ and FAD^+ are electron acceptors.

Answer: (a) Aerobic: needs O_2, complete oxidation, 38 ATP; anaerobic: no O_2, incomplete, 2 ATP. (b) Glycolysis produces pyruvate + 2 ATP + 2 NADH; fermentation converts pyruvate to ethanol/lactic acid, regenerates NAD^+, no extra ATP. (c) Glycolysis is linear in cytoplasm, no CO_2, 2 ATP + 2 NADH; Krebs' cycle is cyclic in mitochondrial matrix, 4 CO_2 per glucose, 2 ATP + 6 NADH + 2 $FADH_2$.

Q8 What are the assumptions made during the calculation of net gain of ATP?

SOLUTION

The following assumptions are made when calculating the theoretical net gain of 38 ATP per glucose molecule during aerobic respiration:

1. Sequential, orderly pathway: It is assumed that glycolysis, TCA cycle, and the ETS pathway function in a strict sequential order, one after another, with one substrate forming the next.
2. Transfer of glycolytic NADH into mitochondria: The 2 NADH produced in glycolysis (in the cytoplasm) are assumed to be transferred into the mitochondria and subjected to oxidative phosphorylation (each yielding 3 ATP). In reality, this transfer involves an energy cost (shuttle mechanisms) that may reduce yield.
3. No withdrawal of intermediates: None of the intermediates of the respiratory pathway are assumed to be withdrawn for biosynthesis of other compounds (amino acids, fatty acids, nucleotides, etc.).
4. Only glucose as substrate: It is assumed that only glucose is being respired and no alternative substrates (fats, proteins) are entering the pathway at any intermediate stage.

These assumptions are not valid in a living cell, where all pathways operate simultaneously, intermediates are constantly being diverted, ATP is consumed as needed, and enzyme activity is regulated by multiple factors. Hence, the figure of 38 ATP is a theoretical maximum.

Answer: Assumptions: (1) glycolysis, TCA, and ETS proceed sequentially; (2) glycolytic NADH is transported into mitochondria for oxidative phosphorylation; (3) no intermediates are diverted for biosynthesis; (4) only glucose is used as the respiratory substrate. These conditions do not hold in a living cell, so 38 ATP is a theoretical value.

Q9 Discuss "The respiratory pathway is an amphibolic pathway."

SOLUTION

The term 'amphibolic' means a pathway involved in both catabolism (breakdown) and anabolism (synthesis). Classically, respiration was considered only a catabolic pathway because it involves the breakdown of glucose and other organic molecules to release energy. However, the respiratory pathway is now recognised as amphibolic because its intermediates serve as starting materials

for biosynthesis.

How respiration serves catabolism:
Fats are broken down to glycerol and fatty acids. Fatty acids are degraded to acetyl CoA and enter the Krebs' cycle. Glycerol is converted to PGAL and enters glycolysis. Proteins are hydrolysed by proteases; amino acids (after deamination) enter the pathway as pyruvate, acetyl CoA, or as specific Krebs' cycle intermediates, depending on their carbon skeleton.

How respiration serves anabolism:
Acetyl CoA, when withdrawn from the respiratory pathway, is used for fatty acid synthesis. Alpha-ketoglutarate and oxaloacetate (OAA), intermediates of Krebs' cycle, are used for synthesis of glutamate and aspartate (amino acids), respectively. PGAL from glycolysis is used for synthesis of glycerol (for fat synthesis). Pyruvate can be used for synthesis of alanine.

Therefore, the respiratory pathway acts as a central hub that connects the breakdown of carbohydrates, fats, and proteins (catabolism) with the synthesis of fatty acids, amino acids, and other biomolecules (anabolism). This dual role makes it an amphibolic pathway rather than a purely catabolic one.

Answer: The respiratory pathway is amphibolic because it participates in both catabolism (breakdown of glucose, fats, proteins to yield energy) and anabolism (its intermediates — acetyl CoA, OAA, alpha-ketoglutarate, PGAL — are withdrawn for synthesis of fatty acids, amino acids, and glycerol). The same pathway thus serves both breakdown and biosynthesis, making it amphibolic.

Q10 Define RQ. What is its value for fats?

SOLUTION

Respiratory Quotient (RQ), also called the respiratory ratio, is the ratio of the volume of CO_2 evolved to the volume of O_2 consumed during aerobic respiration.

RQ = Volume of CO_2 evolved / Volume of O_2 consumed

The RQ depends on the type of respiratory substrate being oxidised:
- Carbohydrates: RQ = 1.0 (equal volumes of CO_2 and O_2)
- Proteins: RQ approximately 0.9
- Fats: RQ less than 1.0

For fats, RQ is less than 1 because fats are relatively hydrogen-rich and

oxygen-poor compared to carbohydrates. More O_2 is consumed to oxidise the large number of C-H bonds, while proportionally less CO_2 is released.

Example calculation for tripalmitin (a fat):

$2C_{51}H_{98}O_6 + 145O_2 \rightarrow 102CO_2 + 98H_2O + \text{energy}$

RQ = 102 CO_2 / 145 O_2 = 0.7

The RQ value for fats is approximately 0.7.

Answer: RQ (Respiratory Quotient) = Volume of CO_2 evolved / Volume of O_2 consumed. It indicates the type of substrate being respired. For fats, RQ is approximately 0.7 (e.g., tripalmitin: 102 CO_2 / 145 O_2 = 0.7) — less than 1 because fats require proportionally more O_2 to oxidise their hydrogen-rich carbon chains.

Q11 What is oxidative phosphorylation?

SOLUTION

Oxidative phosphorylation is the process by which ATP is synthesised using the energy released during the oxidation of NADH and $FADH_2$ through the electron transport system (ETS), in the presence of O_2.

Mechanism:

1. NADH and $FADH_2$, produced during glycolysis, pyruvate oxidation, and the Krebs' cycle, donate their electrons to the ETS on the inner mitochondrial membrane.
2. As electrons pass through the complexes (I --> ubiquinone --> III --> cytochrome c --> IV), the energy released is used to pump protons (H^+) from the mitochondrial matrix into the intermembrane space, establishing an electrochemical proton gradient.
3. Protons flow back into the matrix through ATP synthase (Complex V), which consists of F0 (proton channel in the membrane) and F1 (the catalytic headpiece in the matrix). The flow of $4H^+$ through F0 drives the synthesis of 1 ATP from ADP and inorganic phosphate at the F1 site.
4. O_2 acts as the final electron acceptor at complex IV, getting reduced to H_2O.

This process is called 'oxidative' because it is driven by the oxidation of NADH and $FADH_2$, and 'phosphorylation' because it results in the addition of a phosphate group to ADP to form ATP.

It is distinct from photophosphorylation (which uses light energy) and from substrate-level phosphorylation (where ATP is directly synthesised during a

metabolic reaction).

Yield: Each NADH produces 3 ATP; each FADH2 produces 2 ATP via oxidative phosphorylation.

Answer: Oxidative phosphorylation is the synthesis of ATP from ADP + Pi using the energy of the proton gradient generated by NADH/FADH2 oxidation through the ETS on the inner mitochondrial membrane. Protons flow back through ATP synthase (F0F1 complex), driving ATP synthesis. O2 is the final electron acceptor, forming H2O. Each NADH yields 3 ATP; each FADH2 yields 2 ATP.

Q12 What is the significance of step-wise release of energy in respiration?

SOLUTION

If glucose were oxidised all at once (as in combustion), all the energy would be released as heat in a single uncontrolled burst. This would be wasteful and damaging to the cell. The step-wise release of energy during cellular respiration is significant for the following reasons:

1. Efficient energy capture (ATP synthesis): Because energy is released in small, controlled steps, it can be coupled to ATP synthesis at specific exergonic steps. This allows a much greater proportion of the total energy in glucose to be trapped as ATP (usable energy) rather than being lost as heat. The theoretical maximum is 38 ATP per glucose in aerobic respiration.

2. Prevention of cellular damage: A sudden large release of energy (as in combustion) would damage or denature cellular components including proteins, membranes, and nucleic acids. The gradual, controlled release prevents this.

3. Regulation and control: Step-wise reactions, each controlled by specific enzymes, allow the cell to regulate the rate of energy release according to its needs. Enzymatic control at each step ensures that respiration is adjusted in response to the cell's demand for ATP.

4. Production of useful intermediates: The step-wise degradation generates a variety of carbon skeleton intermediates (pyruvate, acetyl CoA, alpha-ketoglutarate, OAA, PGAL, etc.) that serve as precursors for the biosynthesis of amino acids, fatty acids, nucleotides, and other essential biomolecules. This dual role makes the pathway amphibolic.

5. Maintenance of body temperature: In warm-blooded animals, the heat

produced as a by-product of step-wise respiration helps maintain body temperature within a physiological range.

In summary, step-wise release of energy ensures maximum efficiency, safety, regulation, and biochemical versatility for the cell.

Answer: Step-wise release allows: (1) efficient ATP synthesis by coupling energy release to phosphorylation at specific steps (38 ATP per glucose theoretically); (2) prevention of cellular damage from sudden heat release; (3) enzymatic regulation of energy release according to cellular need; (4) generation of biosynthetic intermediates (acetyl CoA, OAA, PGAL) for anabolic reactions. A single-step oxidation like combustion would waste all energy as heat.