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Introduction

Overview

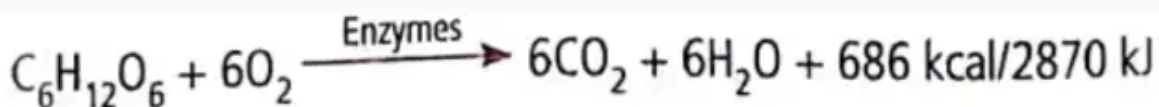
- All living organisms need energy for life activities like absorption, transport, movement, reproduction, and breathing.
- Energy is obtained by oxidation of food.
- Plants are autotrophic; they make food by photosynthesis.
- Animals are heterotrophic; they get food from plants directly (herbivores) or indirectly (carnivores).
- Cellular respiration is the oxidation of complex compounds inside cells to release energy.
- Respiratory substrates are compounds oxidised during respiration, mainly carbohydrates, but also proteins, fats, and organic acids in some cases.
- Energy release occurs in slow, enzyme-controlled steps, trapping energy as ATP, the cell's energy currency.
- Respiration is an enzymatically controlled, stepwise oxidative breakdown of food inside living cells.

Memory Aids

- ATP = Energy currency of the cell.
- Photosynthesis = Food source for all life.
- Respiratory substrates = Mainly carbohydrates.

Quick Checkpoints

- What is the main source of energy for life processes?
- Define cellular respiration.
- What is ATP and its role?



Cellular Respiration Equation

Explanation

- Glucose ($C_6H_{12}O_6$) combines with oxygen (O_2).
- Enzymes break down glucose.
- Produces carbon dioxide (CO_2) and water (H_2O).
- Releases energy: 686 kcal or 2870 kJ.
- Energy is used by cells for various functions.

Memory Aids

- Glucose + Oxygen $\rightarrow$ CO_2 + H_2O + Energy.
- Energy release is stepwise and enzyme-controlled.

Quick Checkpoints

- What are the products of cellular respiration?
- How is energy released during respiration?
- What role do enzymes play in respiration?

Do Plants Breathe?

Gas Exchange in Plants

- Plants require oxygen for respiration and release carbon dioxide.
- They lack specialised respiratory organs but use stomata and lenticels for gas exchange.
- Each plant part manages its own gas exchange; little gas transport between parts.
- Plants have lower respiration rates than animals.
- During photosynthesis, oxygen is produced inside cells, ensuring availability.
- Gases diffuse easily due to loose packing of parenchyma cells creating air spaces near the surface.
- Complete glucose combustion requires oxygen, producing CO_2 , H_2O , and heat energy.

- Some organisms perform anaerobic respiration when oxygen is absent: facultative anaerobes can switch, obligate anaerobes cannot.
- Glucose oxidation occurs in small steps to couple energy release with ATP synthesis.
- Respiration products: carbon dioxide, water, and energy.

Memory Aids

- Stomata and lenticels = Plant gas exchange sites.
- Parenchyma cells = Air space network for diffusion.
- Facultative vs obligate anaerobes = Oxygen use flexibility.

Quick Checkpoints

- How do plants exchange gases without respiratory organs?
- What structures facilitate gas exchange in plants?
- What happens during anaerobic respiration?

Glycolysis

Pathway Overview

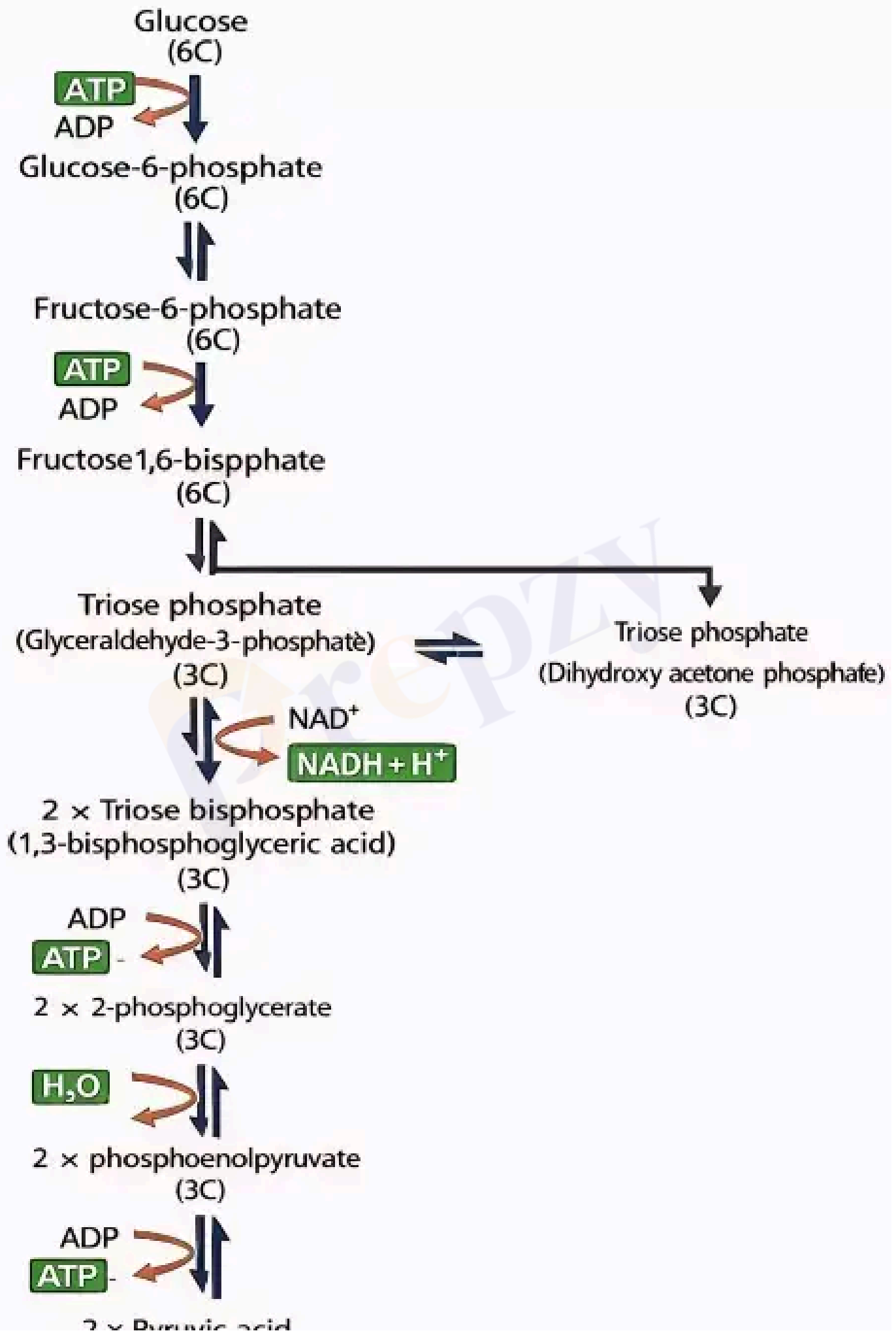
- Glycolysis means "splitting sugar" from Greek words glycos (sugar) and lysis (splitting).
- Also called EMP pathway after Embden, Meyerhof, and Parnas.
- Occurs in cytoplasm; universal in all biological systems.
- One glucose molecule partially oxidized to form two pyruvate molecules.
- In plants, glucose comes from sucrose (photosynthesis product) or storage carbohydrates.
- Sucrose converted to glucose and fructose by invertase enzyme before entering glycolysis.

Sequential Steps

- Glucose phosphorylated to glucose-6-phosphate by ATP using hexokinase or glucokinase and Mg^{2+} .
- Glucose-6-phosphate isomerized to fructose-6-phosphate by phosphohexose isomerase.

- Fructose-6-phosphate phosphorylated to fructose-1,6-bisphosphate by phosphofructokinase (rate-limiting step), ATP and Mg^{2+} involved.
- Fructose-1,6-bisphosphate split into glyceraldehyde-3-phosphate (PGAL) and dihydroxyacetone phosphate (DHAP) by aldolase.
- DHAP isomerized to glyceraldehyde-3-phosphate by triose phosphate isomerase.
- Glyceraldehyde-3-phosphate oxidized; NAD^+ reduced to $NADH + H^+$; inorganic phosphate added to form 1,3-bisphosphoglycerate by glyceraldehyde phosphate dehydrogenase.
- 1,3-bisphosphoglycerate donates phosphate to ADP forming ATP and 3-phosphoglycerate by phosphoglycerate kinase (substrate-level phosphorylation).
- 3-phosphoglycerate converted to 2-phosphoglycerate by phosphoglyceromutase (phosphate shift from 3rd to 2nd carbon).
- 2-phosphoglycerate converted to phosphoenolpyruvate (PEP) by enolase.
- PEP transfers phosphate to ADP forming ATP and pyruvate by pyruvate kinase.





2. Pyruvic acid (3C)

Fig.: Steps of glycolysis

Energy Yield and Fate

- 2 ATP used, 4 ATP produced; net gain = 2 ATP.
- 2 NADH formed; each NADH equals 3 ATP; total ATP gain = 8 ATP.
- End product pyruvate has three fates: fermentation (anaerobic), aerobic respiration, or biosynthesis.
- Intermediates used for synthesis of amino acids (tryptophan, tyrosine, phenylalanine) and other biochemicals.
- Pyruvate forms alanine amino acid.

Memory Aids

- EMP pathway named after Embden, Meyerhof, Parnas.
- Phosphofructokinase step is rate-limiting and irreversible.
- Substrate-level phosphorylation occurs at phosphoglycerate kinase and pyruvate kinase steps.
- NADH formed during glyceraldehyde-3-phosphate oxidation.

Quick Checkpoints

- What is the location of glycolysis in the cell?
- Which enzyme catalyzes the rate-limiting step?
- How many ATP molecules are net gained in glycolysis?
- What are the end products of glycolysis?
- Which intermediates are used for amino acid synthesis?

Fermentation

Process and Types

- Fermentation is anaerobic incomplete oxidation of glucose.

- Yeast converts pyruvic acid to ethanol and CO₂ using enzymes pyruvic acid decarboxylase and alcohol dehydrogenase.
- Some bacteria and animal muscles produce lactic acid from pyruvic acid via lactate dehydrogenase when oxygen is low.
- NADH + H⁺ is oxidized back to NAD⁺ in both alcoholic and lactic acid fermentation.
- Energy yield is low; less than 7% of glucose energy is released and not fully captured as ATP.
- Fermentation produces hazardous products: acid or alcohol.
- Yeasts die when alcohol concentration reaches about 13%.

Memory Aids

- Alcoholic fermentation: yeast + pyruvate = ethanol + CO₂.
- Lactic acid fermentation: muscles + pyruvate = lactic acid.
- NADH recycling is key for glycolysis continuation.

Quick Checkpoints

- What enzymes catalyze alcoholic fermentation?
- How is NAD⁺ regenerated in fermentation?
- Why is fermentation less efficient than aerobic respiration?
- What limits yeast survival in fermentation?

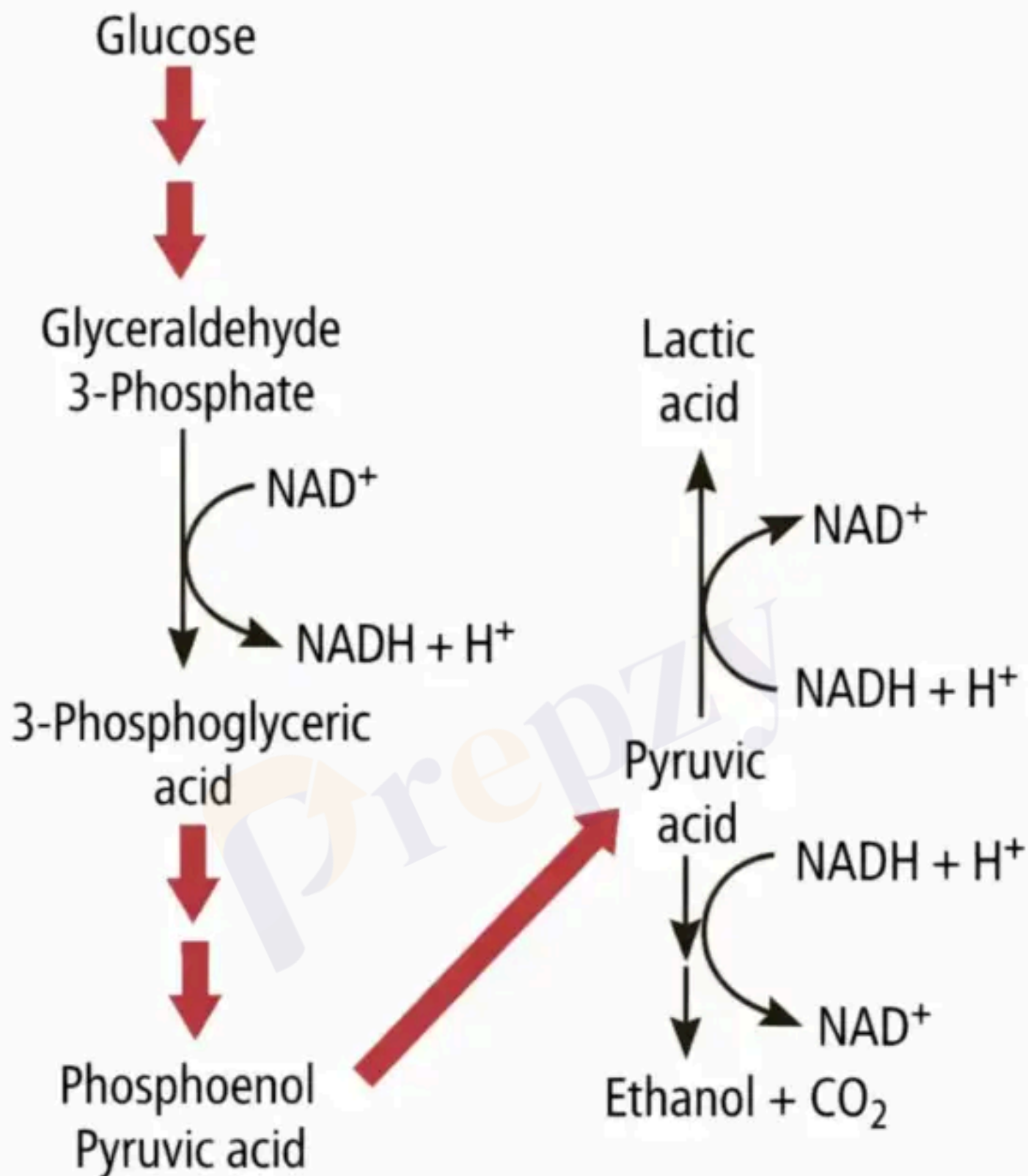


Fig.: Major pathways of anaerobic respiration

Pathways and Applications

- Glucose breaks down to glyceraldehyde 3-phosphate, then to 3-phosphoglyceric acid, phosphoenol pyruvic acid, and pyruvic acid.
- Pyruvic acid converts to either lactic acid or ethanol + CO₂, regenerating NAD⁺.
- Regeneration of NAD⁺ allows glycolysis to continue without oxygen.
- Alcoholic fermentation by *Saccharomyces cerevisiae* is used in brewing beer, rum, whisky.
- Fermentation occurs in germinating barley seeds due to increased sugar.

Memory Aids

- Glycolysis intermediates lead to pyruvate, then to fermentation products.
- Brewing yeast = *Saccharomyces cerevisiae*.
- Germinating seeds ferment due to sugar rise.

Quick Checkpoints

- What are the end products of pyruvate in fermentation?
- Which yeast species is used in brewing?
- Why does fermentation occur in germinating seeds?

Aerobic Respiration

Process Overview

- Complete oxidation of organic substances in presence of oxygen.
- Releases carbon dioxide, water, and large energy amount.
- Occurs mainly in mitochondria of higher organisms.
- Pyruvate from glycolysis transported from cytoplasm to mitochondria.
- Two key events: oxidation of pyruvate to CO₂ and transfer of electrons to O₂ with ATP synthesis.
- Oxidation occurs in mitochondrial matrix; electron transfer on inner mitochondrial membrane.

Memory Aids

- "Oxygen is final electron acceptor"
- "Pyruvate links glycolysis and Krebs cycle"

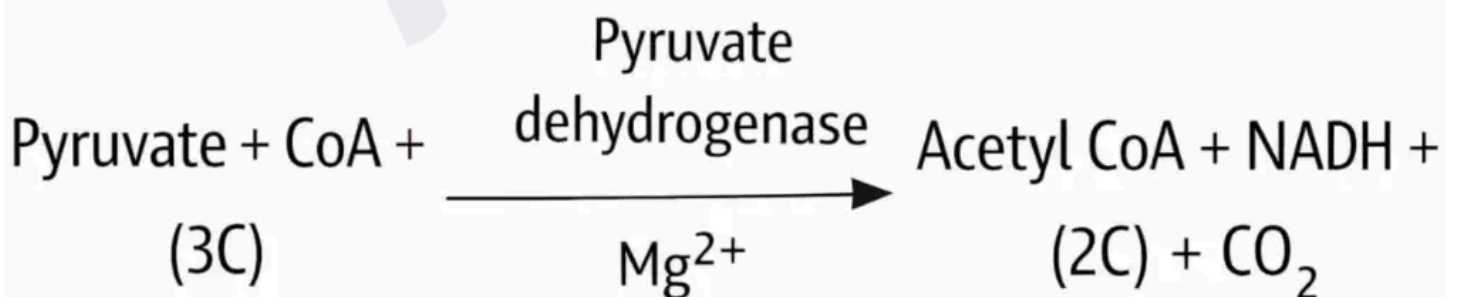
Quick Checkpoints

- Where does aerobic respiration occur?
- What is the fate of pyruvate in mitochondria?
- What are the two main processes in aerobic respiration?

Pyruvate Oxidation

Key Steps

- Pyruvate enters mitochondrial matrix via transport protein.
- Oxidative decarboxylation produces CO₂ and NADH.
- Acetyl CoA formed by combining product with coenzyme A.
- Enzyme complex pyruvate dehydrogenase catalyzes reaction.
- Called gateway or link reaction connecting glycolysis to Krebs cycle.



Memory Aids

- "Pyruvate + CoA = Acetyl CoA"
- "Mg²⁺ needed for enzyme activity"

Quick Checkpoints

- What enzyme catalyzes pyruvate oxidation?
- What are the products of pyruvate oxidation?
- Why is this step called the link reaction?

Krebs Cycle

Steps and Features

- Proposed by Hans Adolf Krebs in 1937.
- Occurs in mitochondrial matrix with respiratory enzymes.
- Acetyl CoA (2C) + oxaloacetate (4C) → citrate (6C) via citrate synthase (condensation).
- Citrate → cis-aconitate + water (dehydration) via aconitase.
- Cis-aconitate + water → isocitrate (hydration) via aconitase.
- Isocitrate → oxalosuccinate + NADH (dehydrogenation I) via isocitrate dehydrogenase.
- Oxalosuccinate → α -ketoglutarate + CO₂ (decarboxylation I).
- α -Ketoglutarate → succinyl CoA + NADH + CO₂ (dehydrogenation II and decarboxylation II) via α -ketoglutarate dehydrogenase.
- Succinyl CoA → succinic acid + GTP (substrate level phosphorylation) via succinyl synthetase.
- Succinic acid → fumaric acid + FADH₂ (dehydrogenation) via succinic dehydrogenase.
- Fumarate + water → malate (hydration II) via fumarase.
- Malate → oxaloacetate + NADH (dehydrogenation IV) via malate dehydrogenase.
- Oxaloacetate repeats cycle by combining with acetyl CoA.
- Two pyruvate molecules yield 2 ATP, 8 NADH, 2 FADH₂.
- Cycle is amphibolic: provides intermediates for anabolic pathways.

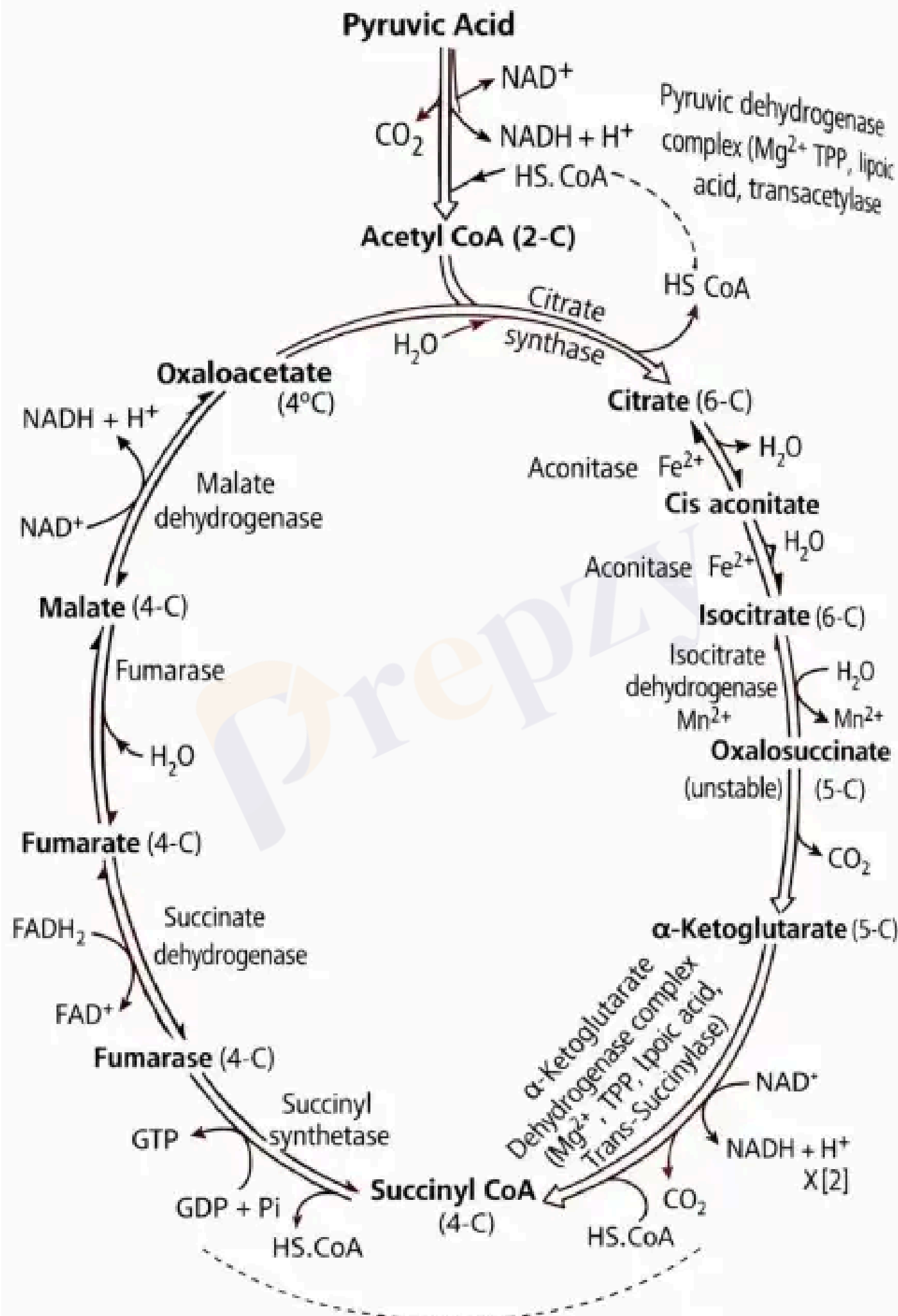


Fig.: Schematic representation of Krebs' cycle or TCA cycle

Memory Aids

- "Citrate is first product"
- "Cycle produces NADH, FADH₂, GTP"
- "Amphibolic: catabolism + anabolism"

Quick Checkpoints

- What is the first product of Krebs cycle?
- Which enzyme catalyzes succinyl CoA to succinate?
- Why is Krebs cycle called amphibolic?

Electron Transport Chain

Process Details

- Oxidation of NADH and FADH₂ releases energy.
- Electrons pass through complexes I to IV in inner mitochondrial membrane.
- NADH oxidized by NADH dehydrogenase (complex I), electrons to ubiquinone.
- FADH₂ electrons enter via complex II to ubiquinone.
- Ubiquinone transfers electrons to cytochrome c via complex III.
- Cytochrome c transfers electrons to complex IV (cytochrome c oxidase).
- Electrons reduce oxygen to water at complex IV.
- Electron flow coupled to ATP synthase (complex V) producing ATP from ADP and Pi.
- One NADH yields 3 ATP; one FADH₂ yields 2 ATP.
- Oxygen is final electron and hydrogen acceptor.
- Electron flow pumps protons from matrix to intermembrane space, creating proton gradient.
- Proton gradient creates electrochemical potential called proton motive force.
- Inhibitors: cyanide blocks electron transfer to oxygen; antimycin blocks between cytochrome b and c; dinitrophenol uncouples electron transport and ATP synthesis.

Inter-membrane
space

Inner Mitochondrial
membrane

Matrix

4H^+

$\text{NADH} + \text{H}^+$

NAD^+

(Fe-S)

FMN

I

e^-

Complex I
(NADH dehydrognase)

UQ

e^-

UQH_2

4H^+

III

e^-

Cyt

Fe-S

Cyt c_1

Complex II
(Succinate dehydrngnase)

Cyt c

UQH_2

UQ

e^-

Cyt c

(Fe-S)

AQ

$\text{O}_2 + 2\text{H}^+$

H_2O

Complex III
(Succinate dehydrognase)

4H^+

Ca_3

Ga_3

$[\text{Cj}-\text{a}_1$

$\text{MIO}_{2\text{a}}$

Complex IV
(Cytochrome c oxidase)

ADP

ATP

F_0

F_1

ATP
synthase

ATP

ATP

H^+

Electrostatic F_0

Electrochemical

Fig.: Electron Transport System (ETS)

Memory Aids

- "ETS complexes I-IV transfer electrons"
- "Oxygen is terminal electron acceptor"
- "Proton motive force drives ATP synthesis"

Quick Checkpoints

- What is the role of oxygen in ETS?
- How many ATP molecules are produced per NADH?
- What creates the proton motive force?

Oxidative Phosphorylation

Mechanism

- ATP synthesis using energy from oxidation of NADH and FADH₂.
- Different from photophosphorylation (uses light energy).
- ATP synthase (complex V) activated by proton gradient in intermembrane space.
- ATP synthase has two parts: F₁ (catalytic) and F₀ (proton channel).
- Protons flow through F₀, causing F₁ to synthesize ATP from ADP and Pi.
- 4 protons pass per ATP produced.
- Proton flow driven by electrochemical gradient (proton motive force).
- Process called chemiosmotic ATP synthesis (Peter Mitchell, 1961).

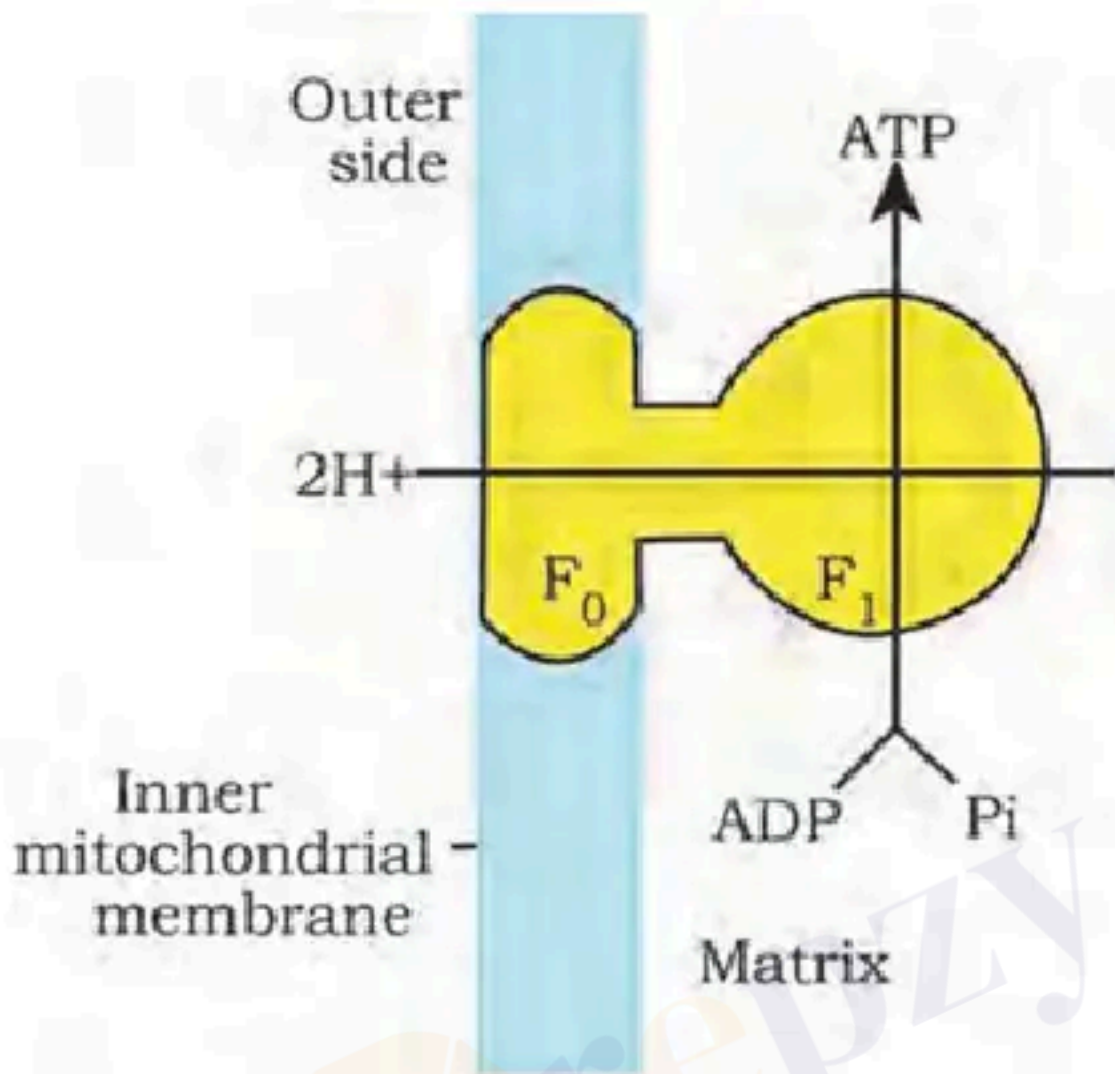


Figure Diagrammatic presentation of ATP synthesis in mitochondria

Memory Aids

- "F₀ forms proton channel"
- "F₁ synthesizes ATP"
- "Chemiosmotic mechanism"

Quick Checkpoints

- What activates ATP synthase?
- How many protons are needed per ATP?

- Who proposed chemiosmotic theory?

Respiratory Balance Sheet

Key Assumptions

- Sequential pathway: glycolysis, TCA cycle, and ETS occur in order.
- NADH from glycolysis enters mitochondria for oxidative phosphorylation.
- Intermediates are not diverted for other biosyntheses.
- Only glucose is respired; no alternative substrates enter the pathway.

Reality in Cells

- Pathways operate simultaneously, not sequentially.
- Substrates enter and leave pathways as needed.
- ATP usage and enzyme activity are tightly regulated.

ATP Yield

- Maximum theoretical yield: 38 ATP per glucose molecule during aerobic respiration.
- Fermentation yields only 2 ATP per glucose, partial glucose breakdown.
- Aerobic respiration fully degrades glucose to CO_2 and H_2O .
- NADH reoxidation is slow in fermentation, rapid in aerobic respiration.

ATP Molecules Produced During Respiration

Stage of Respiration	Source	ATP Produced
Glycolysis	Direct synthesis	2
	2 NADH (1 NADH = 3 ATP)	6
Pyruvic acid → Acetyl-CoA	2 NADH	6
Citric Acid Cycle (Krebs Cycle)	6 NADH	18
	2 FADH ₂ (1 FADH ₂ = 2 ATP)	4
	Direct synthesis	2
Total Yield		38 ATP

Memory Aids

- "Sequential assumptions rarely hold in cells"
- "38 ATP max in aerobic, 2 ATP in fermentation"
- "Aerobic = complete glucose breakdown"

Quick Checkpoints

- What assumptions are made in ATP yield calculations?
- How do real cellular pathways differ from theoretical models?
- Compare ATP yield in fermentation vs aerobic respiration.
- Why is NADH reoxidation faster in aerobic respiration?

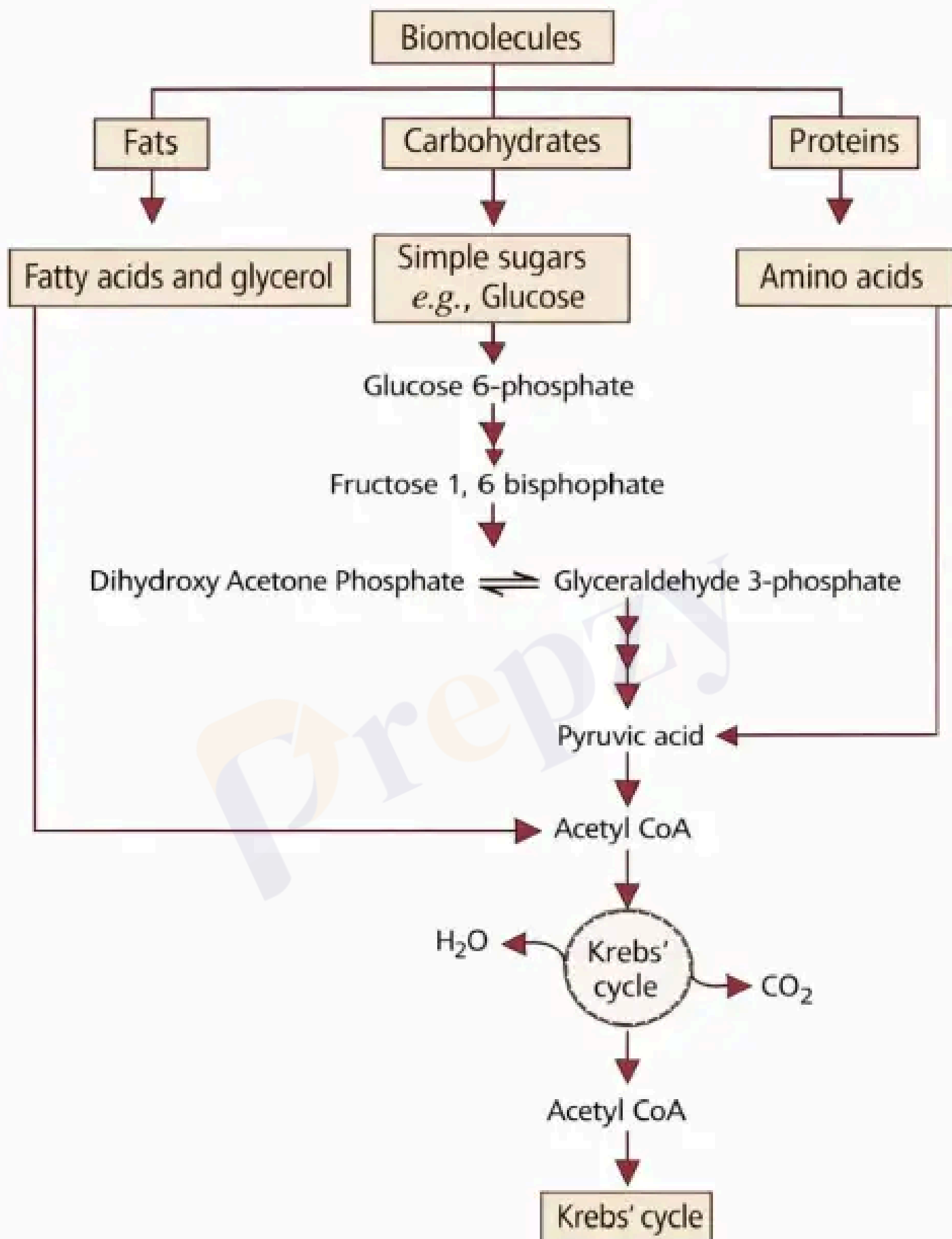
Amphibolic Pathway

Subtopics

- Glucose is the preferred substrate for respiration; all carbohydrates convert to glucose first.

- Other substrates like fats and proteins enter the respiratory pathway later, not at the first step.
- Fats break down into glycerol and fatty acids; fatty acids convert to acetyl CoA, glycerol converts to PGAL before entering the pathway.
- Proteins are degraded by proteases into amino acids; after deamination, amino acids enter the pathway as pyruvate, acetyl CoA, or Krebs cycle intermediates.
- The respiratory pathway is involved in both breakdown (catabolism) and synthesis (anabolism) of molecules.
- Acetyl CoA can be withdrawn from the pathway for fatty acid synthesis.
- Respiratory intermediates link breakdown and synthesis of proteins.
- Because it functions in both catabolism and anabolism, the respiratory pathway is called an amphibolic pathway.

Prepzy



Memory Aids

- Glucose first, others later.
- Fats → glycerol + fatty acids → acetyl CoA.
- Proteins → amino acids → deamination → Krebs cycle entry.
- Respiration = both breakdown + synthesis = amphibolic.

Quick Checkpoints

- What is the main substrate for respiration?
- How do fats enter the respiratory pathway?
- What happens to amino acids before entering respiration?
- Why is the respiratory pathway called amphibolic?

Prepzy