Cellular Respiration

I. An Overview of Cell Respiration

A. Cell respiration is a decomposition pathway that provides energy (ATP) by oxidizing organic foods into CO_2 and H_2O.

1. In aerobic respiration, oxygen is the oxidizing agent that gets e^- from the decomposed food.

a. $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$

b. One glucose releases more energy than is needed for a single reaction, so many ATP are formed instead.

2. Anaerobic respiration occurs without O_2, using a waste product, a N compound, or a S cmpd. instead.

a. The food is not fully decomposed so it does not release as much energy.

b. Many organisms can store the reduced, energy rich waste products for use later.

B. There are four main stages of aerobic respiration that take place in two parts of the cell.

1. Glycolysis (in cytoplasm) partially oxidizes glucose into two 3-C compounds, releasing a small amount of ATP.

2. The 3-C compounds enter mitochondria, lose a CO_2 (now 2-C) and are bound by coenzyme A.

3. Coenzyme A delivers the 2-C compounds to the Krebs cycle in the matrix of mitochondria.

a. The 2-C compounds are completely oxidized into CO_2.

b. The energy released is used to form some ATP and to reduce NAD^+ into NADH and FAD^+ into $FADH_2$.

4. Still in the mitochondria, NADH & $FADH_2$ drop off e^- and protons at an electron transport chain.

a. High energy e^- are used to actively transport H^+ ions across a membrane (diffusion for lots of ATP).

b. Oxygen accepts the e^- at the end of the e.t.c. and combines with hydrogen to form water.

c. Lack of oxygen as an e^- acceptor backs up (shuts down) both Krebs cycle and the e.t.c.

II. The Reactions of Respiration

A. Glycolysis begins both aerobic and anaerobic respiration.

1. Two enzymatic steps each use an ATP to modify glucose.

2. The 6C molecule now splits into 2 – 3C sugar phosphates. (PGAL may enter here; carbon skeletons available)

3. More enzymatic reactions partially oxidize the two sugar phosphates into two molecules of pyruvate (3C).

a. 2 NADH and 4 ATP are formed.

b. Net yield: 2 NADH and 2 ATP.

4. If sufficient O_2 is present, each pyruvate will go on to a mitochondrion.

5. Insufficient O_2 causes fermentation of pyruvate.

a. NAD^+ is needed for the ATP yielding steps of glycolysis to occur.

b. NADH reduces pyruvate into lactate, alcohol, or acetic acid (vinegar), providing the needed NAD^+.

B. Once inside a mitochondrion, pyruvate must be converted before any carbon is added to the Krebs cycle.

1. Enzymes cause pyruvate to release a molecule of CO_2, forming acetic acid (2C).

2. Acetic acid is oxidized (reducing NAD^+), forming acetate.

3. Coenzyme A binds to acetate (now acetyl-CoA) and delivers it to the Krebs cycle in the matrix.

C. The Krebs cycle completely oxidizes acetate.

1. CoA drops acetate off which is picked up by a 4C compound (oxaloacetate), forming the 6C compound citrate.

2. A series of enzymatic reactions form the following:

a. 2 CO_2

b. 3 NADH and 1 $FADH_2$

c. 1 ATP

3. 2 acetate from each glucose → double products above

4. The end of the Krebs cycle regenerates oxaloacetate.

D. The electron transport chains use NADH and $FADH_2$ to produce ATP.

1. Cytochromes (e^- transport proteins) imbedded in the inner mitochondrial membrane separate H atoms into protons (left in the matrix) and electrons.

2. As e^- are passed down the chain, the energy they release allows enzymes to actively transport protons. $\Uparrow[H^+]$

3. The H^+ diffuse through ATP synthetase → ATP.

4. Each NADH provides enough energy for 3 ATP while each $FADH_2$ yields 2 ATP.

5. O_2 is the final e- acceptor – if it is not available, the e.t.c. clogs up and will not operate.

E. Various species have varying needs for O_2.

1. Obligate aerobes (us included) can't survive long w/o O_2.

2. Obligate anaerobes use glycolysis and/or fermentation for all their energy needs (O_2 can be poisonous).

3. Facultative aerobes generally prefer to use aerobic resp., but can go for long periods of time w/ anaerobic resp.

III. Respiration and Cellular Activities

A. Fats and proteins may also be used to generate ATP.

1. When lipids are broken down, glycerol enters glycolysis while the fatty acids are converted into acetate.

a. Glycerol can contribute to anaerobic processes.

b. The fatty acids must have O_2 available to become oxidized in the Krebs cycle.

2. Before they are used for energy, proteins must be broken into amino acids and have the amine group removed.

a. NH_3 is formed and is usually converted to urea or uric acid before excretion from the body.

b. The resulting 4C (oxaloacetate) or 5C (ketogluterate) acids can enter the Krebs cycle.

B. Like glycolysis, compounds can be removed from the Krebs cycle to provide carbon skeletons for biosynthesis.

C. Many organisms use respiration for heat production.

1. Warm blooded animals release enough heat to keep their body temperature fairly stable.

2. Alternate respiration pathways in specialized mitochondria release more heat and less ATP than normal.

a. Brown fat (LOTS of mito's) can rapidly raise the temperature of hibernating, small, and/or hairless animals.

b. Some plants have an alternate e.t.c. branch which raises their temp. for producing odors (pollination) or melting snow.

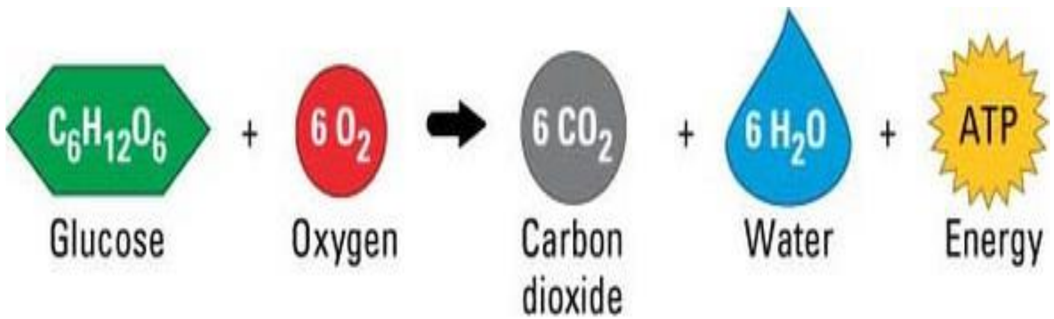
D. The rate of respiration is controlled by supply and demand.

1. When energy demands are low, excess blood glucose is converted to glycogen or fat.

2. When demands are high, glycogen is broken down to supply blood glucose (fats and proteins may also be used, especially when glycogen supply runs low).

Cellular Respiration

- Cellular respiration is the process which cells take the energy from glucose to function.
- During respiration, cells break down simple food molecules such as glucose and release the energy they contain.



- The food involved in respiration is usually glucose
- Internal respiration is controlled by enzymes which allow energy to be released in small amounts
- The energy is trapped in molecules called ATP

Steps of Cellular Respiration

1. Starts off in the cytoplasm of cells. Glucose is broken down into smaller molecules.

2. Next part takes place in the mitochondria. Molecules are broken down even smaller. This reaction requires oxygen, and a great deal of energy is released.

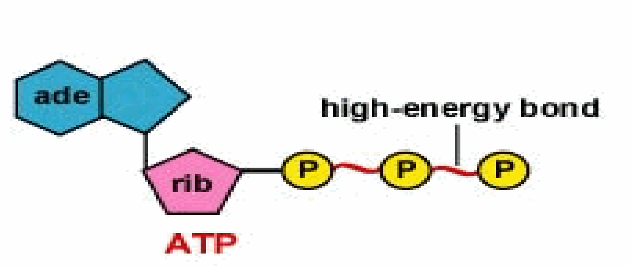
3. The end product is carbon dioxide and water. These products diffuse out of the cell.

4. This is why when you breathe in, you take in oxygen. When you breathe out, you release carbon dioxide and water.

Aerobic Respiration

- Most living things get energy from aerobic respiration and are called **AEROBES**

- The energy stored in bonds in glucose is released and used to make ATP



- When ATP breaks down it supplies energy for all the reactions in a cell, such as movement of muscles, growth of new cells etc.

Equation for Aerobic Respiration

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{ATP (energy)}$$

Glucose + Oxygen ⟶ Carbon dioxide + water + energy

- Aerobic respiration is relatively efficient, 40% of the energy in glucose is used to make ATP

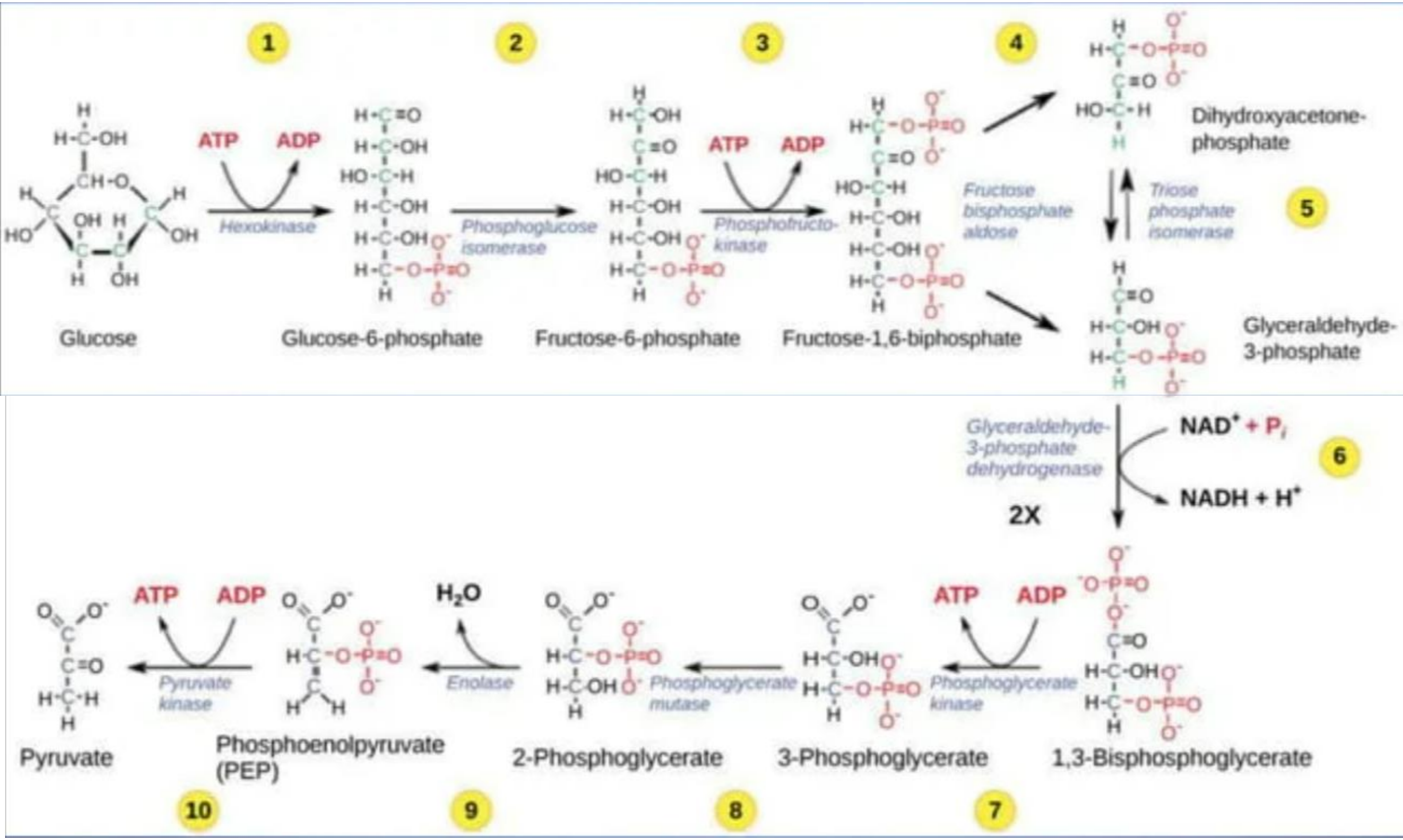
- Any energy not used to produce ATP is lost as heat

Aerobic Respiration occurs in multiple stages

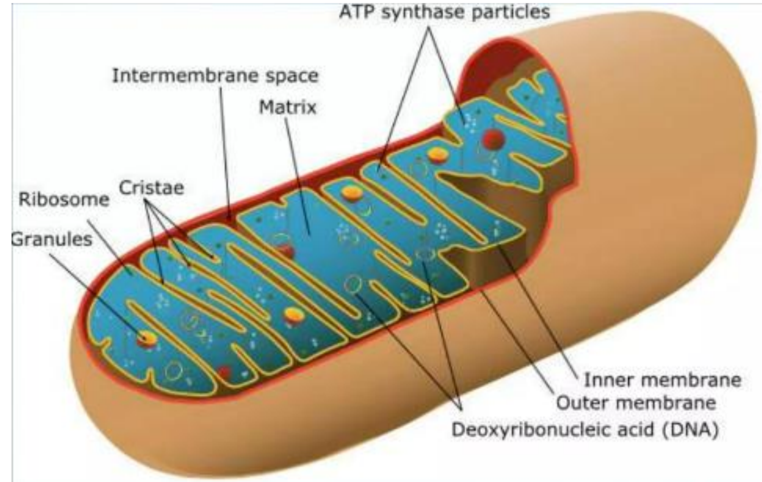
- Stage 1 ------------- Glycolysis
- Stage 2 ------------- Kreb Cycle
- ------------- Electron transport chain

Satge 1: Glycolysis

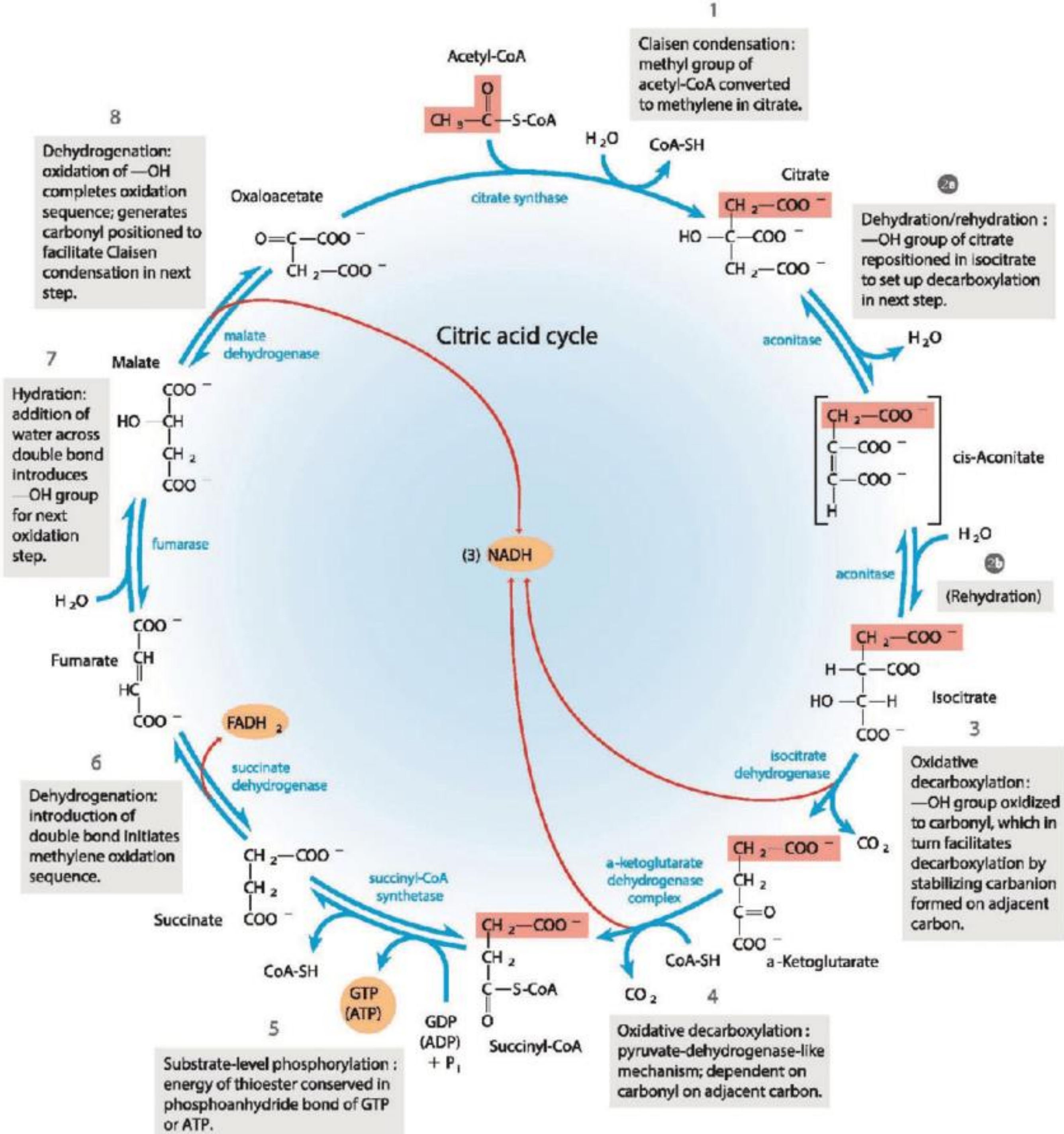
- Takes place in the cytosol (the cytoplasm without the organelles) as enzymes are found here
- Does not require oxygen
- It only releases small amounts of energy
- Is the same for both aerobic and anaerobic respiration
- A 6 carbon carbohydrate (Glucose) is converted to two 3 carbon molecules with the release of a small amount of energy
- Most of the energy in the glucose molecule remains stored in each 3- carbon molecule


1
2
3
4
5
6
7
8
9
10
ATP
ADP
Hexokinase
Phosphoglucose isomerase
Phosphofructo-kinase
Fructose bisphosphate aldose
Triose phosphate isomerase
Glucose
Glucose-6-phosphate
Fructose-6-phosphate
Fructose-1,6-biphosphate
Dihydroxyacetone-phosphate
Glyceraldehyde-3-phosphate
Glyceraldehyde-3-phosphate dehydrogenase
NAD+ + Pi
NADH + H+
2X
H_2O
Pyruvate kinase
Enolase
Phosphoglycerate mutase
Phosphoglycerate kinase
Pyruvate
Phosphoenolpyruvate (PEP)
2-Phosphoglycerate
3-Phosphoglycerate
1,3-Bisphosphoglycerate

Stage 2

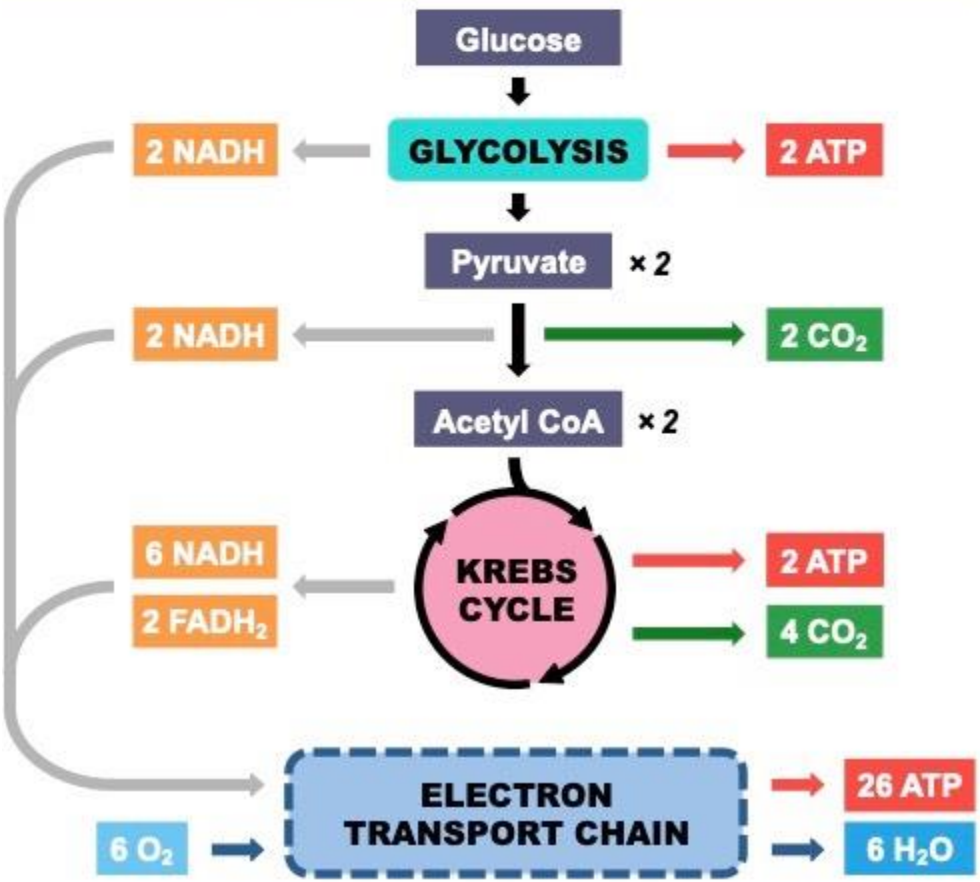


- This stage requires and uses oxygen
- It releases a large amount of energy
- It occurs in the mitochondria as the necessary enzymes are found here
- The 3- carbon molecules are broken down to Carbon Dioxide and Water
- The complete breakdown of the 3-carbon molecules releases a lot of energy
- There is very little energy left in Carbon Dioxide and Water



Citric acid cycle
1
Claisen condensation: methyl group of acetyl-CoA converted to methylene in citrate.
Acetyl-CoA
H2O
CoA-SH
citrate synthase
Citrate
Dehydration/rehydration: —OH group of citrate repositioned in isocitrate to set up decarboxylation in next step.
aconitase
H2O
cis-Aconitate
H2O
aconitase
(Rehydration)
Isocitrate
3
Oxidative decarboxylation: —OH group oxidized to carbonyl, which in turn facilitates decarboxylation by stabilizing carbanion formed on adjacent carbon.
isocitrate dehydrogenase
CO2
a-Ketoglutarate
a-ketoglutarate dehydrogenase complex
CoA-SH
CO2
4
Oxidative decarboxylation: pyruvate-dehydrogenase-like mechanism; dependent on carbonyl on adjacent carbon.
Succinyl-CoA
succinyl-CoA synthetase
GDP (ADP) + Pi
GTP (ATP)
CoA-SH
5
Substrate-level phosphorylation: energy of thioester conserved in phosphoanhydride bond of GTP or ATP.
Succinate
succinate dehydrogenase
FADH2
6
Dehydrogenation: introduction of double bond initiates methylene oxidation sequence.
Fumarate
H2O
fumarase
7
Hydration: addition of water across double bond introduces —OH group for next oxidation step.
Malate
malate dehydrogenase
8
Dehydrogenation: oxidation of —OH completes oxidation sequence; generates carbonyl positioned to facilitate Claisen condensation in next step.
Oxaloacetate
(3) NADH

Overview of the Aerobic Reaction Process



Summary of the Molecular Conversions

STAGE	**GLYCOLYSIS** *(anaerobic)*	**KREBS CYCLE** *(aerobic)*	**ETC** *(aerobic)*
SITE	Cytosol	Matrix	Cristae
REACTION	Glucose → 2 Pyruvate	2 Pyruvate → $6 CO_2$	$6 O_2$ → $6 H_2O$
CARRIERS	2 NADH *(small yield)*	8 NADH, $2 FADH_2$ *(large yield)*	*All carriers are oxidised to make ATP*
ATP	2 ATP *Substrate level phosphorylation*	2 ATP *Substrate level phosphorylation*	26 ATP *Oxidative phosphorylation*

Anaerobic Respiration

- Anaerobic respiration can occur in the presence of oxygen, but it does not need to use it
- In anaerobic respiration, Glycolysis occurs this means glucose is broken into two 3-carbon molecules
- A small amount of energy is released this way
- There are different forms of anaerobic respiration where the 3 – carbon molecules are converted to different substances, but no extra energy is released
- Anaerobic respiration is said to be less efficient than aerobic respiration as less energy is released

Fermentation

- Anaerobic Respiration is also known as Fermentation

- 2 types of fermentation

1. Lactic Acid Fermentation
2. Alcohol Fermentation

Lactic Acid Fermentation

- This occurs in some anaerobic bacteria and fungi and in animal muscles when there is not enough oxygen
- In this fermentation Lactic acid is produced
- **Glucose $\longrightarrow$ 2 Lactic Acid + small amount of energy**
- Lactic acid forms when bacteria cause milk to go sour, when bacteria respire on cabbage to form Sauerkraut, in silage production and in yoghurt production
- When we exercise and get out of breath not enough oxygen can reach our muscles and anaerobic respiration takes place in the muscle this forms lactic acid which causes cramps, when you rest the lactic acid is broken down by the liver.

Alcohol Fermentation

- Takes place in Bacteria and some fungi such as yeast and in plants when they are deprived of oxygen
- Involves the partial breakdown of glucose

- Glucose $\longrightarrow$ 2 Ethanol + 2 Carbon dioxide + small amount of energy

- The ethanol itself is high energy

- Alcohol fermentation has been used for centuries

- If baking yeast is used for alcohol fermentation, the alcohol evaporates but the carbon dioxide causes the dough to rise

- Baking powder is used instead of yeast in very hot ovens

Industrial Fermentation

- **Biotechnology** refers to the use of living things (such as microorganisms and enzymes) to carry our useful reactions
- In industrial fermentation the microorganisms are placed in a container with a suitable substrate on which they can react
- The vessel in which biological reactions can take place is called a **Bioreactor**

A fermentation bioreactor

Differences between Aerobic and Anaerobic Respiration

	Aerobic	Anaerobic
Location	Cytoplasm and Lumen and Cristae of mitochondria	Cytoplasm
Oxygen Requirements	Uses O_2	Does not use O_2
End Products	$CO_2 + H_2O$	Ethanol +CO_2 or Lactic acid
Energy Produced	Lots of energy (38 ATP)	Little energy (2 ATP)