Physiology of fungi

For the 4th year of B.Sc. students

Prepared by

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Introduction

Fungal physiology refers to the nutrition, metabolism, growth, reproduction and death of fungal cells. It also generally relates to interaction of fungi with their biotic and abiotic environment, including cellular responses to stress. The physiology of fungal cells impacts significantly on the environment, industrial processes and human health. In relation to ecological aspects, the biogeochemical cycling of carbon in nature would not be possible without the participation of fungi acting as primary decomposers of organic material. Furthermore, in agricultural operations, fungi play important roles as mutualistic symbionts, pathogens and saprophytes, where they mobilize nutrients and affect the physico-chemical environment. Fungal metabolism is also responsible for the detoxification of organic pollutants and for bioremediating heavy metals in the environment. The production of many economically important industrial commodities relies on the exploitation of yeast and fungal metabolism, and these include such diverse products as whole foods, food additives, fermented beverages, antibiotics, probiotics, pigments, pharmaceuticals, biofuels, enzymes, vitamins, organic and fatty acids and sterols. In terms of human health, some yeasts and fungi represent major opportunistic life-threatening pathogens, whilst others are life-savers, as they provide antimicrobial and chemotherapeutic agents. In modern biotechnology, several yeast species are being exploited as ideal hosts for the expression of human therapeutic proteins following recombinant DNA technology. In addition to the direct industrial exploitation of yeasts and fungi, it is important to note that these organisms, most notably the yeast *Saccharomyces cerevisiae*, play increasingly significant roles as model eukaryotic cells in furthering our fundamental knowledge of biological and biomedical science. This is especially the case now that numerous fungal genomes have been completely sequenced, and the information gleaned from fungal genomics and proteomics is

providing valuable insight into human genetics and heritable disorders. However, knowledge of cell physiology is essential if the functions of many of the currently unknown fungal genes are to be fully elucidated. It is apparent, therefore, that fungi are important organisms for human society, health and well-being and that studies of fungal physiology are very pertinent to our understanding, control and exploitation of this group of microorganisms. This course describes some basic aspects of fungal cell physiology, focusing on fungal cell structure, nutrition, growth and metabolism in fungi.

Culture media

Classification of culture media

Criteria used for classifying culture media includes their chemical composition, physical properties and their use. Every culture medium is designed for a definite use and hence its physical and chemical characteristics depend on its application and function.

I- Classification of culture media according to their use

According to their use culture media are divided into the following types:

1- **Routine laboratory media**: These media contain certain complex raw materials of plant or animal origin such as yeast extract, malt extract, peptone etc., and are employed for routine cultivation and maintenance of a wide variety of fungi.

2- Enriched media: These media are prepared by supplementing the routine laboratory media with some specific substances such as vitamins and amino acids to meet the nutritional requirements of more fastidious of fungi and are employed for their cultivation.

3- Selective media: These media facilitate the isolation of a particular group or species of microorganisms from mixed cultures. Such media contain substances which inhibit microorganisms except the desired group or species, such as mannitol salt agar and tellurite media.

4- Differential media: These media are supplemented with certain reagents or chemicals for differentiating between various kinds of microorganisms on the basis of visible differences in their growth patterns. Such type of media is used more often in bacteriological studies such as eosin methylene blue agar and deoxycholate citrate agar.

5- Assay media: These type of media is specifically employed for the assay of some metabolites such as enzymes, vitamins, amino acids, antibiotics, disinfectants etc., and are of definite composition.

6- Biochemical media: These media are generally used for the differentiation of microorganisms on the basis of their biochemical activities, and are helpful in the study of their metabolic processes.

II- Classification of culture media according to their chemical composition: According to their chemical composition media are classified into the following types:

1- Natural media: The natural medium comprises entirely complex natural products of unknown composition. The raw material of a natural medium may be of plant or animal origin, and some of the common ingredients employed for this purpose include extracts of plant and animal tissues, e.g., fruits, vegetables, egg, milk, blood, body fluids, yeast, malt and manure extracts etc. Obviously, the chemical composition and concentration of a natural medium is not well defined. On account of their complex nature, these media are able to support a variety of organisms, and hence are quite useful for routine laboratory cultures of fungi.

2- Semisynthetic media: These media are so designed that some of their constituents are of known chemical composition, while others are derived from some natural sources with unknown composition. The chemical composition of a semisynthetic medium is partly known. The medium is a best serve as a routine medium and sometimes for physiological studies. Potato dextrose agar (PDA) is one of the popular media.

3- Synthetic media: These are chemically defined media of known composition and concentration. The media are exclusively composed of pure chemical substances. However, absolute purity of the ingredients is achieved, although substances of only analytical reagent quality are used for such purposes. One account of their known composition as well as being in solution, these media are quite useful for nutritional and metabolic studies of fungi. The composition of these media may be amended as per requirement and as such they may be simple or complex in composition. A simple synthetic medium contains a single carbon and energy source, a nitrogen source, generally as ammonium salt, some sulphur and phosphorus sources and various minerals. All these ingredients are dissolved in a buffered aqueous base. However, for more fastidious organisms, a complex synthetic medium is designed by incorporating some additional factors such as certain vitamins, amino-acids, purines, pyrimidines etc., or by employing a multitude of carbon and nitrogen sources together.

C- According to their physical states: Media are classified into the following types:

1- Solid media: Media in solid state are in use since the beginning of laboratory studies of fungi. The first laboratory culture of fungi was obtained on a solid media such as fruit slices. Some common examples of such media are nutrient impregnated slices of potato, carrot, sugar-beet etc. and coagulated egg or serum. However, with the advent of agar as a solidifying agent, such media have largely been replaced by agar media. Use of fruits and vegetable slices in the cultivation of fungi is now more or less restricted to the baiting technique employed for isolation of some specific organisms.

2- Solid-reversible to liquid media: Such reversible media were first introduced by Koch (1881) who observed that addition of 2 to 5 percent of gelatin to the commonly employed media rendered them a semi-solid consistency. However, gelatin could not find a wide application on account of its low melting point (37˚C), and also because it is hydrolyzed by many proteolytic bacteria at

ordinary temperature. The use of agar for solidifying culture media was also initiated the same year and in the same laboratory.

3- Semi-solid media: These are media with gelatinous consistency and are employed for specific purpose. They contain a small amount of agar or some other solidifying agent like corn meal. These media are sometimes used for the study of motile reproductive structures of fungi.

4- Liquid media: These are media without any solidifying agent, and are indispensable for most of the quantitative studies of fungi. Nutritional and metabolic studies of fungi, as well as microbiological assays are invariably carried on liquid media. Some of the advantage of liquid media is that they permit the cultures to be aerated, the mycelium to be weighed and the metabolic products to be analyzed easily. However, with respect to routine studies, liquid media have some distinct disadvantages. Growth in liquid media does not manifest the morphological characteristics of microorganisms. They are also difficult to handle without disturbing the culture. Moreover, liquid media are least helpful in the purification of microorganisms from a mixed culture. For an even distribution of nutrients and for providing uniform aeration to growing fungus, the liquid cultures are sometimes put to constant mechanical shaking.

Sterilization

Sterilization refers to the process that effectively kills or eliminates transmissible agents (such as fungi, bacteria, viruses and spore forms etc.) from a surface, equipment, foods, medications, or biological culture media.

Sterilization can be achieved through application of heat, chemicals, irradiation and filtration.

There are three main methods for sterilization

1- Physical methods

2- Chemical methods

3- Mechanical methods

1- Physical methods

Sterilization by heat

Heat may be utilized for sterilization either in dry or moist form. However, moist heat is much more effective and requires both shorter duration and lower temperature. Sterilization by moist heat generally is complete at 121°C for 15-30 minutes of exposure. On contrast, sterilization by dry heat requires a temperature of 160°C for 60 minutes. The two kinds of heat treatments kill the microorganisms by coagulating and denaturing their enzymes and other proteins.

Application of dry heat

a- Flaming

b- Hot-air oven

c- Radiation (Infra-red or Ultra violet)

Application of moist heat

The use of the Autoclave for sterilization

Chemical methods

Using of chemical substances as agents, like chloroform, mercuric chloride, formaldehyde and ethyl alcohol.

3- Mechanical methods

Sterilization by filtration

This technique employs special type of filters having pores so small that ordinary bacteria are arrested. This method is particularly useful for sterilizing heat sensitive materials, such as culture media containing serum, antibiotic solutions, culture filtrates etc. The most common filters are Seitz filters and Cellulose membrane filters.

Fungal cell structure

Fungi are eukaryotic organisms that include microorganisms such as yeasts, molds and mushrooms. These organisms are classified under kingdom fungi. They are classified as heterotrophs among the living organisms. They are also found in most skin infections and other fungal diseases. Fungi usually grow in places which are moist and warm enough to support them. The structure of fungi can be explained in the following points:

1. Almost all fungi have a filamentous (multicellular) structure except the yeast which are unicellular microorganisms.
2. Fungi consist of long thread-like structures known as hyphae. These hyphae together form a mesh-like structure called mycelium.
3. Fungi possess a cell wall which is made up of chitin and polysaccharides.
4. The cell wall comprises a protoplast, which is differentiated into other cell parts such as cell membrane, cytoplasm, cell organelles and nuclei.
5. The nucleus is dense, clear, with chromatin threads. The nucleus is surrounded by a nuclear membrane.
6. Fungi are eukaryotic, non-vascular, non-motile and heterotrophic organisms.
7. They reproduce by means of spores (sexual or asexual).
8. Fungi exhibit the phenomenon of alternation of generation.
9. Fungi lack chlorophyll and hence cannot perform photosynthesis.

Based on mode of nutrition, fungi can be classified into 3 groups.

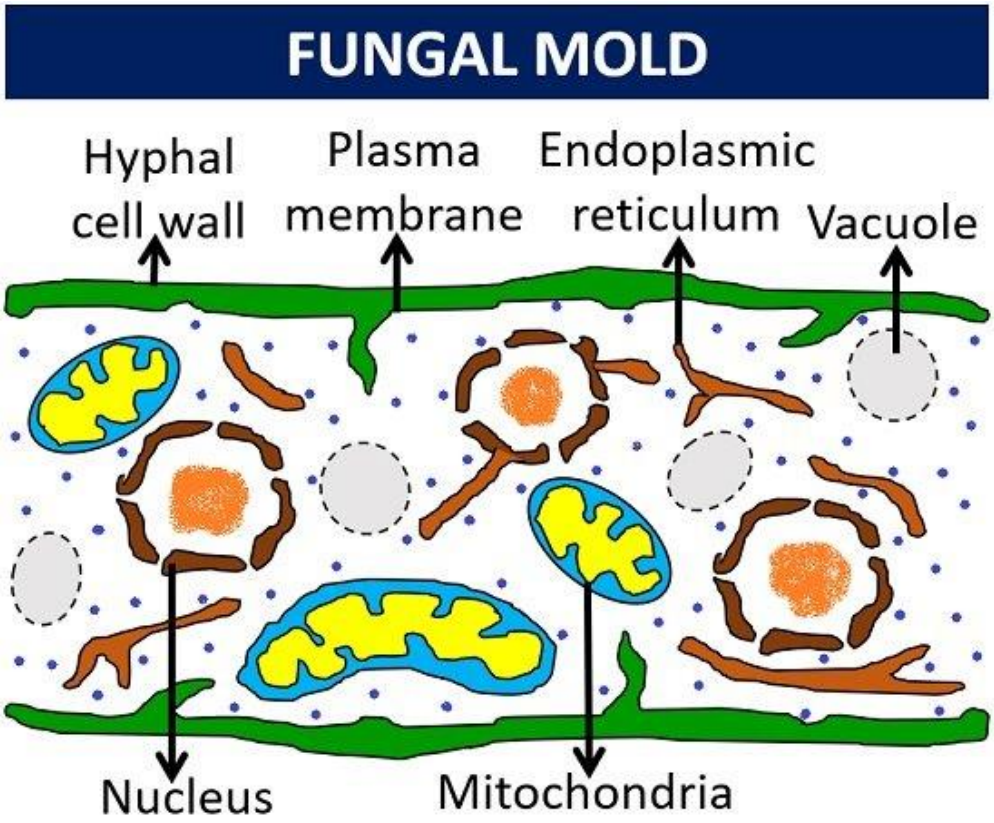
1. **Saprophytic fungi** – The fungi obtain their nutrition by feeding on dead organic substances such as *Aspergillus*, *Penicillium* and *Rhizopus*.
2. **Parasitic fungi**– The fungi obtain their nutrition by living on other living organisms (plants or animals) and absorb nutrients from their host such as *Taphrina* and *Puccinia*.
3. **Symbiotic fungi**–These fungi live with other species in which both are mutually benefited such as Lichens and mycorrhiza. Lichens are the symbiotic association between algae and fungi. Here both algae and fungi are mutually benefited as fungi provide shelter for algae and in reverse algae synthesis carbohydrates for fungi. Mycorrhiza is the symbiotic association present between fungi and plants. Fungi improve nutrient uptake by plants, whereas, plants provide organic molecules like sugar to the fungus.

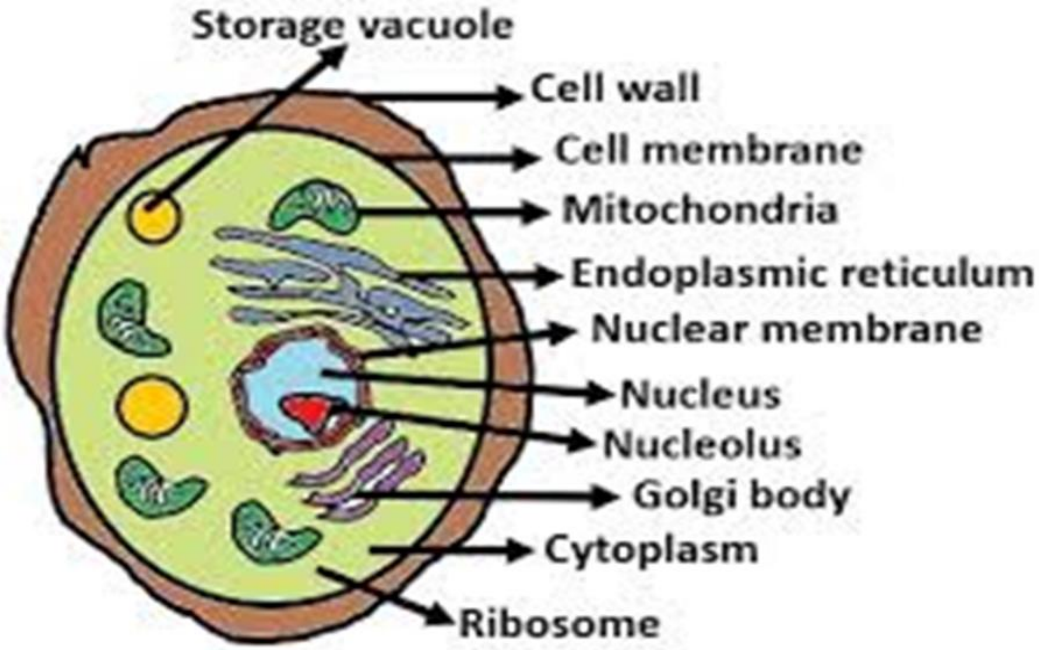
Based on spore formation, Kingdom fungi are classified into the following:

1. **Zygomycetes** – These are formed by the fusion of two different cells. The sexual spores are known as zygospores, while the asexual spores are known as sporangiospores. The hyphae are without septa. Example *Mucor* and *Rhizopus.*
2. **Ascomycetes** – They are also called sac fungi. They can be coprophilous, decomposers, parasitic or saprophytic. The sexual spores are called ascospores. Asexual reproduction occurs by conidiospores. Example – *Saccharomyces*, *Aspergillus* and *Penicillium.*
3. **Basidiomycetes** – Mushrooms are the most commonly found basidiomycetes and mostly live as parasites. Sexual reproduction occurs by basidiospores. Asexual reproduction occurs by conidia, budding or fragmentation. Example- *Agaricus.*
4. **Deuteromycetes** – They are otherwise called imperfect fungi as they do not follow the regular reproduction cycle as the other fungi. They do not

reproduce sexually. Asexual reproduction occurs by conidia. Example – *Alternaria* and *Trichoderma*.

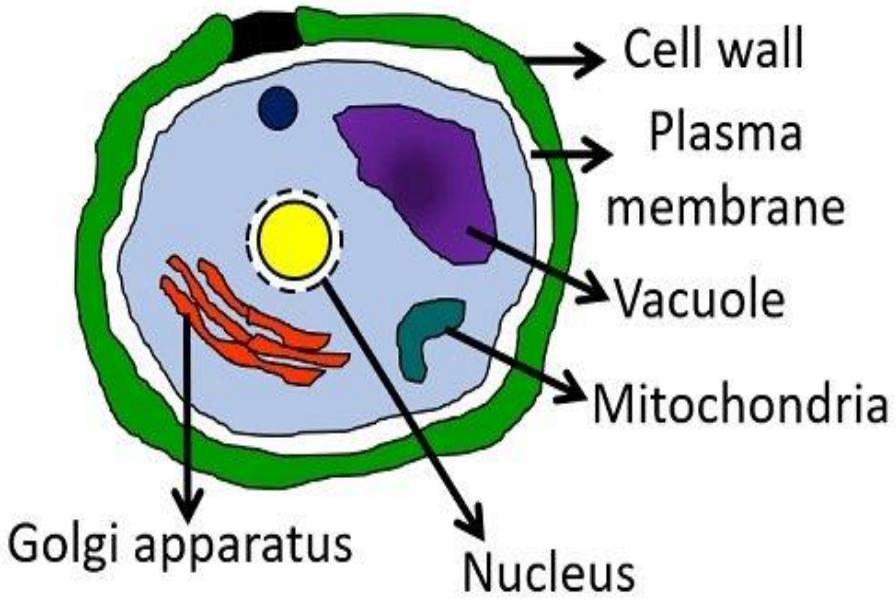
Fungi are eukaryotes and have a complex cellular organization. As eukaryotes, fungal cells contain a membrane-bound nucleus where the DNA is wrapped around histone proteins. A few types of fungi have structures comparable to bacterial plasmids (loops of DNA). Fungal cells also contain mitochondria and a complex system of internal membranes, including the endoplasmic reticulum and Golgi apparatus.





Fungal cell

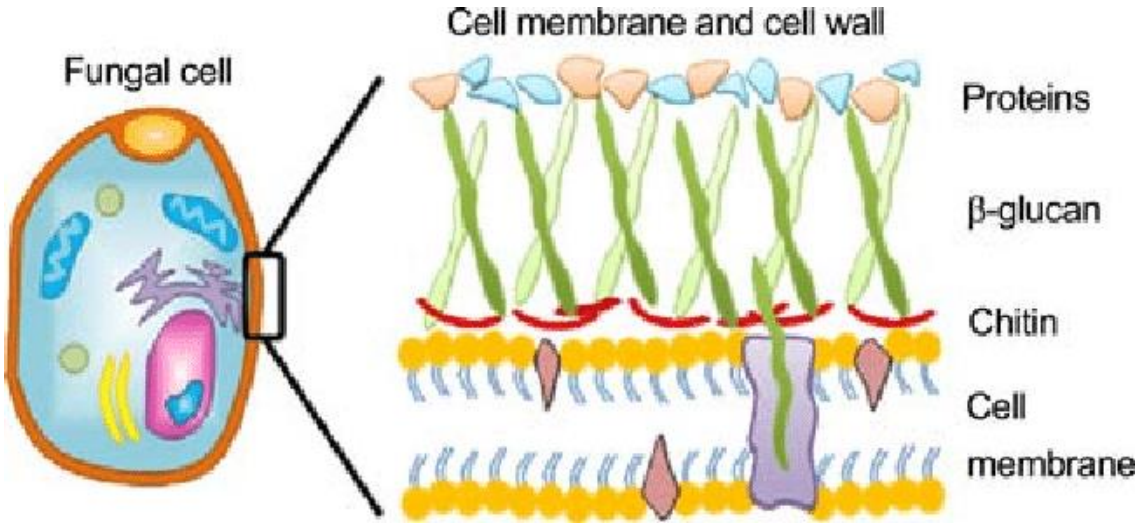
YEAST CELL

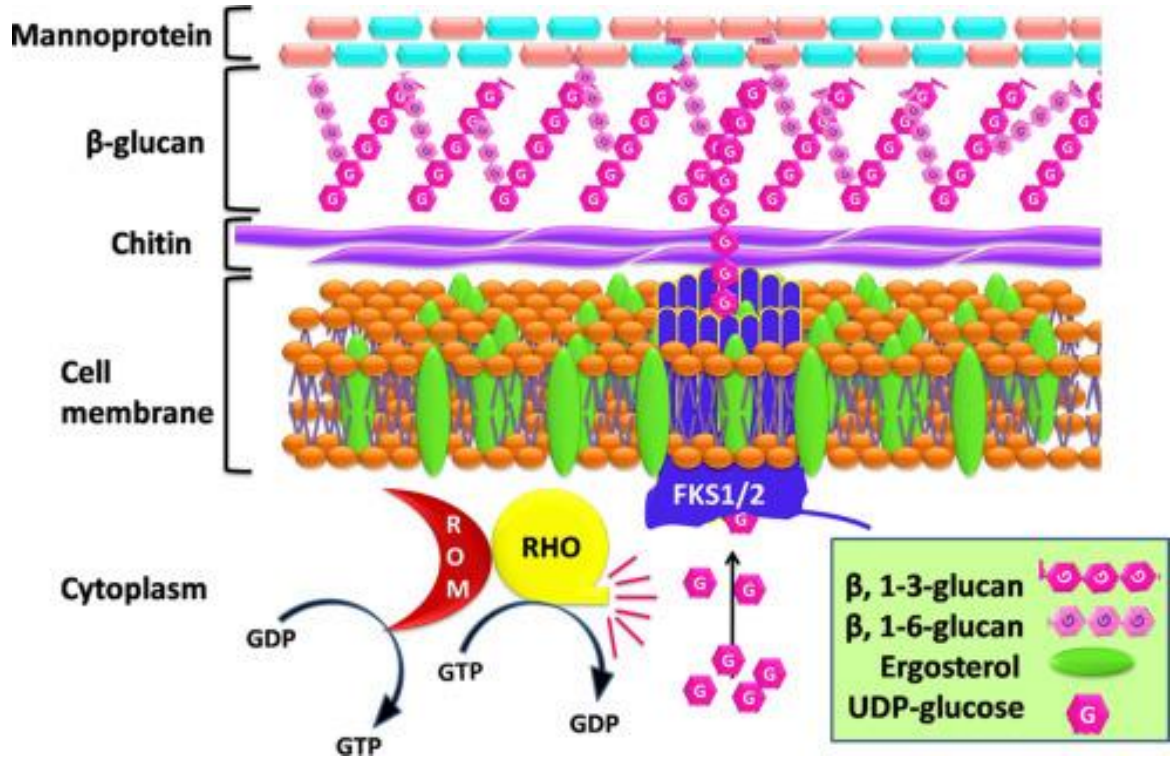


Unlike plant cells, fungal cells do not have chloroplasts or chlorophyll. Many fungi display bright colors arising from other cellular pigments, ranging from red to green to black. The poisonous *Amanita muscaria* (fly agaric) is recognizable by its bright red cap with white patches. Pigments in fungi are associated with the cell wall. They play a protective role against ultraviolet radiation.

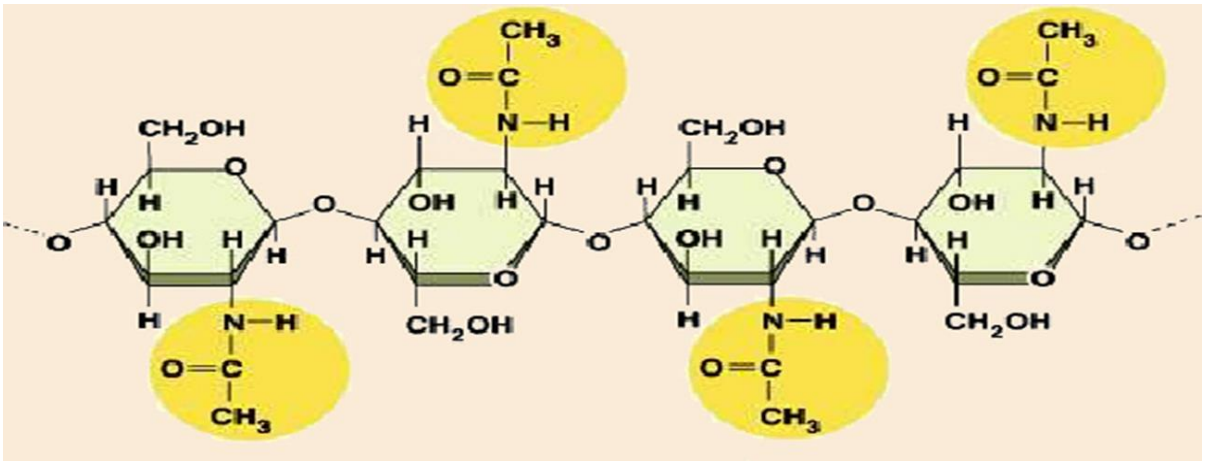
Composition of fungal cell wall

In Eumycota the hyphal cells are bounded by a cell wall. Its composition generally varies in different fungal groups. According to workers like Aronson (1965) and Bartnicki-Garcia (1970) fungal cell walls contain proteins, lipids and 80%-90% polysaccharides. Most common cell wall component is chitin. However, in some fungi cellulose or glucans are present. Cellulose is generally a polymer of D-glucose. According to Bartnicki-Garcia (1968) some other substances associated with the fungal cell wall in different members are cellulose-glycogen, Cellulose-glucan, cellulose-chitin, chitin-glucan, mannan-glucan, mnnan-chitin and polygalactosaminegalactan.





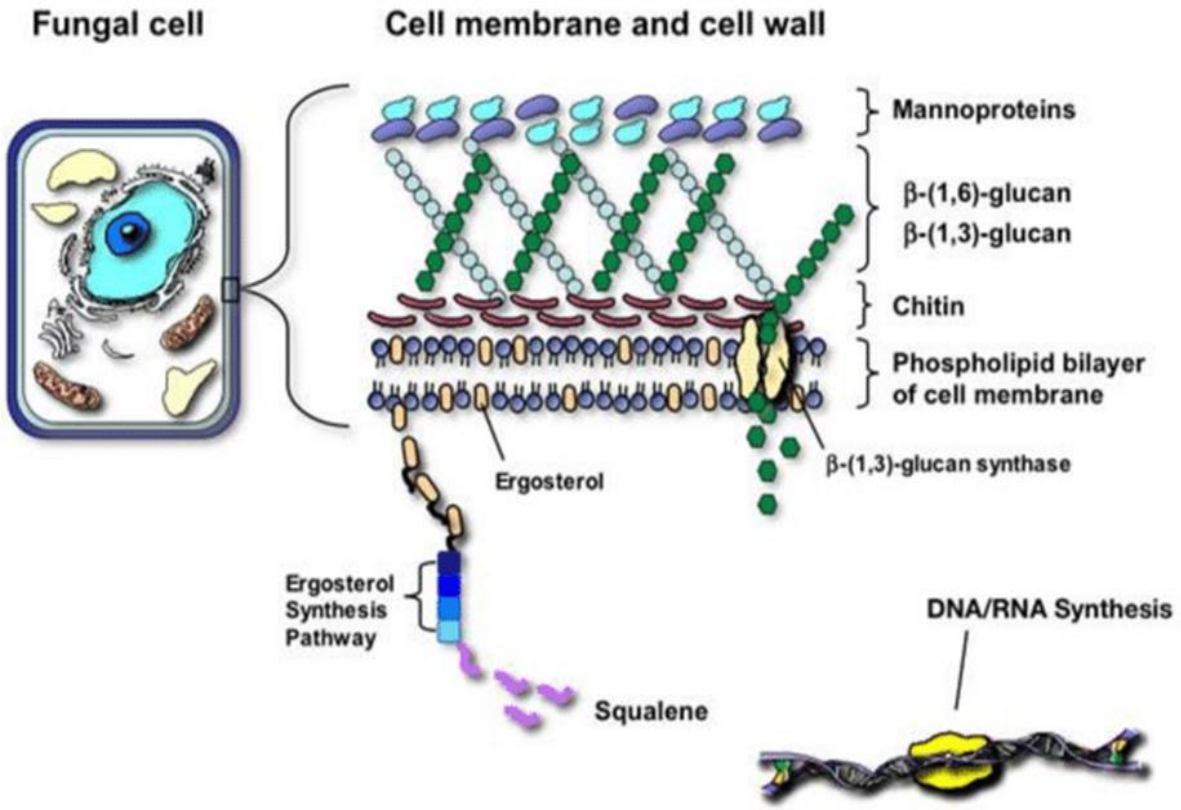
The rigid layers of fungal cell walls contain complex polysaccharides called chitin and glucans. Chitin, also found in the exoskeleton of insects, gives structural strength to the cell walls of fungi. The wall protects the cell from desiccation and predators. Fungi have plasma membranes similar to other eukaryotes, except that the structure is stabilized by ergosterol: a steroid molecule that replaces the cholesterol found in animal cell membranes.



Chitin

Plasma membrane

The plasma membrane, also called the cell membrane, is the membrane found in all cells that separates the interior of the cell from the outside environment. The plasma membrane consists of a bilayer of phospholipid that is semipermeable. The plasma membrane regulates the transport of materials entering and exiting the cell.



Nucleus

The nucleus is bounded by a double nuclear envelope and contains chromatin and a nucleolus. Fungal nuclei are variable in size, shape, and number. The number of chromosomes varies with the particular fungus. *Saccharomyces* cerevisiae, (n=18); *Trichophyton mentagophytes*, (n=4).

Fungal growth and nutrition

When a fungus is added to a suitable liquid medium and incubated at a suitable growth conditions, its growth follows a definite course. If the fungal counts are made at intervals after inoculation and plotted in relation to time, a growth curve obtained shows 4 phases:

Lag phase

Log or Exponential phase

Stationary phase

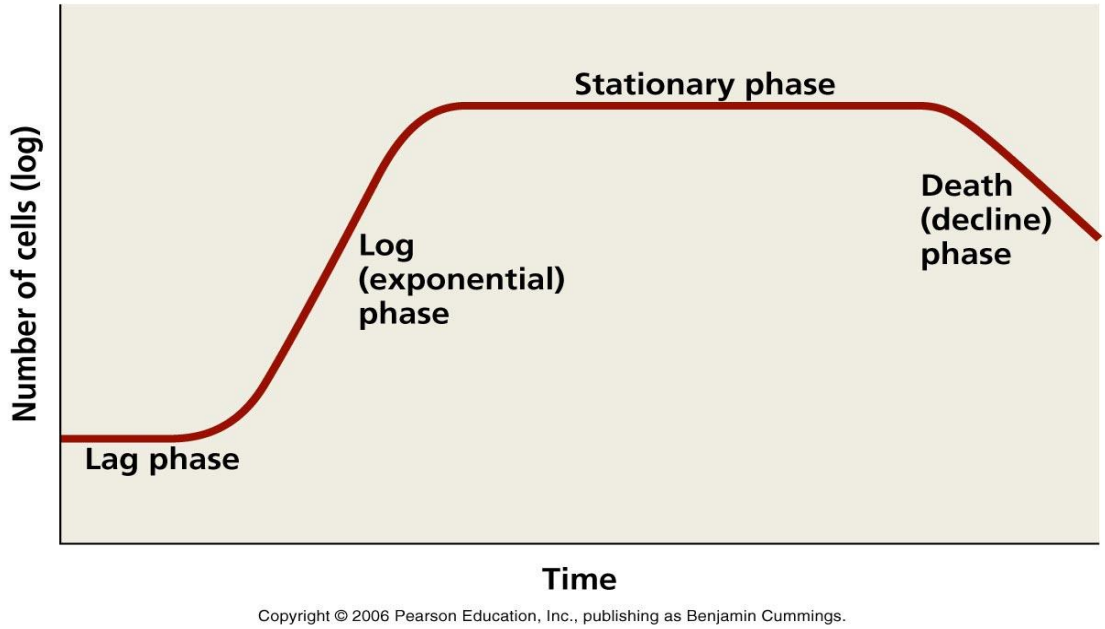
Decline phase

1. Lag phase – No increase in the cell number but there is an increase in the size of the cell. Maximum cell size towards the end of the lag phase

2. Log or exponential phase: cells start dividing and their number increases exponentially. Smaller cells, stain uniformly.

3. Stationary phase: cell division stops due to depletion of nutrients & accumulation of toxic products. Equilibrium exists between dying cells and the newly formed cells, so viable count remains stationary. Irregular staining, sporulation and production of secondary metabolites such as exotoxins & antibiotics.

4. Decline phase: population decreases due to the death of cells – autolytic enzymes. Involution forms (with ageing).



Growth curve of fungi

Factors affecting fungal growth

1- Availability of nutrients & H_2O
2- Temperature
3- Atmosphere – O_2 & CO_2
4- H-ion concentration (pH)

Functions of nutrients

Generation of energy and synthesis of cellular materials.

Essential nutrients (basic bioelements needed for fungal growth).

H_2O: universal solvent; hydrolyzing agent

Carbon: food & energy source; in the form of carbohydrates, proteins and lipids.

Nitrogen: for amino acids and protein synthesis; nucleic acids synthesis (purines & pyrimidines).

Sulfur (sulfate): Some amino acids synthesis such as cystine and methionine.

Phosphate: key component of DNA, RNA and ATP in addition to the formation of phospholipids of the cell membrane.

Minerals: associated with protein (i.e., Fe:PRO); common component of enzymes.

Macronutrients – needed in large quantities for cellular metabolism and basic cell structure such as C, N, H, P and O.

Micronutrients – needed in small quantities; more specialized for enzymes and pigments structure and function such as Fe, Cu, Mn and Zn.

Fastidious fungi: microbes that require other complex - nutrients/growth factors such as vitamins or amino acids.

Factors affecting fungal growth

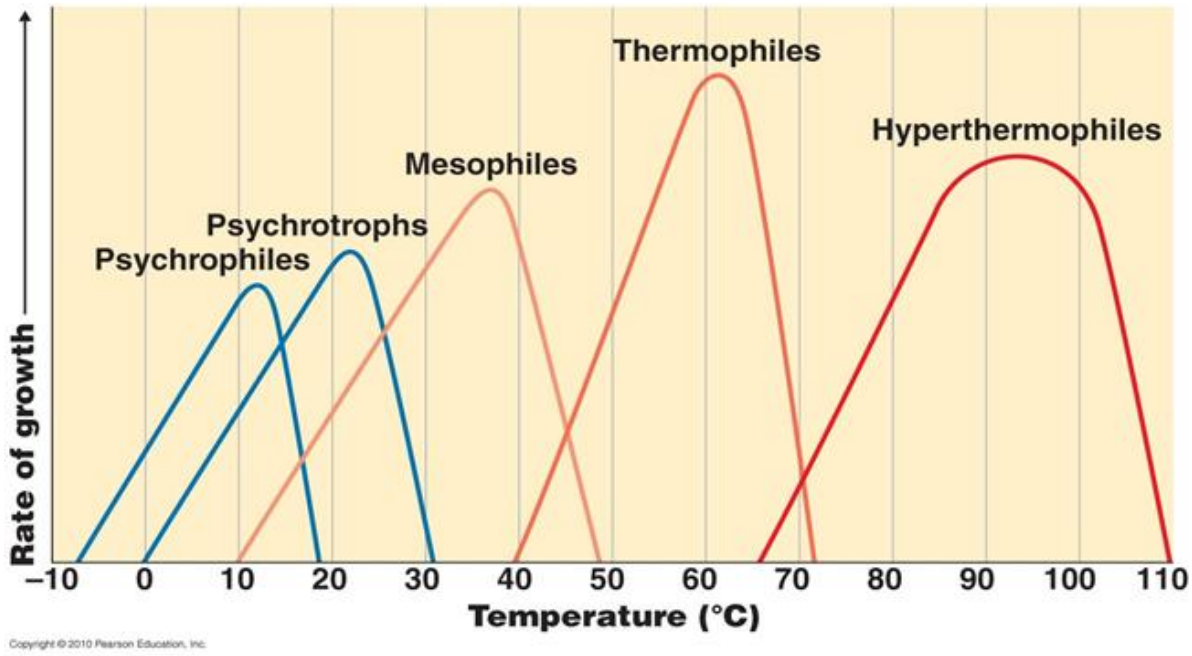
Temperature

Temperature is an important environmental factor affecting growth of molds. Fungi are capable of surviving under the full range of temperatures normally experienced in environments in which they live. The temperature ranges usually reported for fungal growth is broad (10-40°C), with a few species capable of growth below or above this range. Fungi can be divided according to their tolerance to temperature in psychrophilic, mesophilic and thermophilic fungi. Fungi are vary for their temperature requirements. Temperature range - growth does not occur above the maximum or below the minimum.

Minimum temperature – which fungi cannot grow below the minimum temperature.

Optimum temperature – which are the best for fungal growth and metabolism usually within 20-30ºC for most fungi (mesophilic fungi).

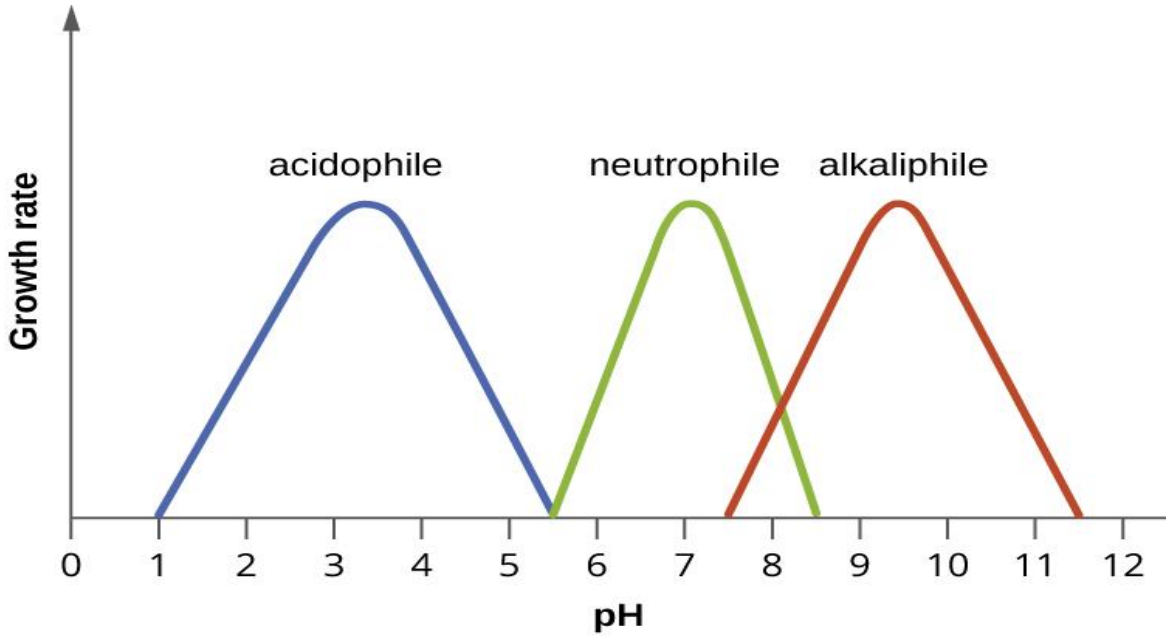
Maximum temperature - which fungi cannot grow above the maximum temperature.



Hydrogen-ion concentration (pH)

Some products such as yogurt, pickles, sauerkraut, and lime-seasoned dishes all owe their tangy taste to a high acid content. The acidity is a function of the concentration of hydrogen ions [H^+] and is measured as pH. Environments with pH values below 7.0 are acidic, with a high concentration of H^+ ions. However, those with pH values above 7.0 are considered basic. Extreme pH affects the structure of all macromolecules. The hydrogen bonds holding together strands of DNA break up at high pH values. Lipids are hydrolyzed by an extremely basic pH. The proton motive force responsible for production of ATP in cellular respiration depends on the concentration gradient of H^+ across the plasma membrane. If H^+ ions are neutralized by hydroxide ions, the concentration gradient collapses and impairs energy production. But the component most sensitive to pH in the cell is its workhorse, the protein. Moderate changes in pH modify the ionization of amino-acid functional groups and disrupt hydrogen bonding, which, in turn, promotes changes in the folding of the molecule, promoting denaturation and destroying activity.

The optimum growth pH is the most favorable pH for the growth of microorganisms. The lowest pH value that an organism can tolerate is called the minimum growth pH and the highest pH is the maximum growth pH. These values can cover a wide range, which is important for the preservation of food and to the microorganism survival in the nature.



The curves show the approximate pH ranges for the growth of the different classes of microorganisms. Each curve has an optimal pH and extreme pH values at which growth is much reduced. Most fungi are neutrophiles and grow best at near-neutral pH. Acidophiles have optimal growth at pH values near 3 and alkaliphiles have optimal growth at pH values above 9.

Neutrophiles

Most fungi are neutrophiles, meaning they grow optimally at a pH within one or two pH units of the neutral pH of 7, between 5 and 9. Also most familiar bacteria, like *Escherichia coli*, *Staphylococci*, and *Salmonella* spp. are neutrophiles and do not fare well in the acidic pH of the stomach. However, there are pathogenic strains of *E. coli*, *S. typhi*, and other species of intestinal pathogens that are much more resistant to stomach acid. In comparison, fungi thrive at slightly acidic pH values of 5.0–6.0.

Acidophiles

Microorganisms that grow optimally at a pH less than 5 are called acidophiles. For example, the sulphur-oxidizing *Sulfolobus* spp. isolated from sulphur mud fields and hot springs in Yellowstone National Park are extreme acidophiles. These archaea survive at pH values of 2.5–3.5. Species of the archaean genus *Ferroplasma* live in acid mine drainage at pH values of 0–2.9. *Lactobacillus* bacteria, which are an important part of the normal microbiota of the vagina, can tolerate acidic environments at pH values 3.5–6.8 and also contribute to the acidity of the vagina (pH of 4, except at the onset of menstruation) through their metabolic production of lactic acid. The vagina's acidity plays an important role in inhibiting other microbes that are less tolerant of acidity. Acidophilic microorganisms display a number of adaptations to survive in strong acidic environments. While the membrane is slightly leaky to protons, the cytoplasmic pH of most acidophiles is generally only slightly acidic. One of the major reasons for this is their ability to actively transport of H^+ ions out of the cell. In addition, cytoplasmic proteins have evolved to function better at a slightly acidic pH with increased negative surface charges compared to their neutrophilic homologues. The ether linkage of the archaeal membrane lipids is more acid stable than the typical ester linked phospholipids, but in addition, acidophilic archaea typically possess tetra ether membrane lipids. The resulting monolayer structure makes their membranes a much better barrier to proton leakage in extremely low pH environments. Since these organisms may also be adapted to growing at high temperatures, the membranes also maintain their semi-fluid consistency. While the cytoplasmic proteins of acidophiles have relatively normal pH optima, those that are secreted have acidic pH optima compared to their neutrophile homologues. The gene sequences for acidophilic secreted proteins have evolved to give secondary, tertiary and quaternary structures that are resistant to the protonating effects of the acidic environment. These proteins are of great interest for their possible biotechnological applications.

Alkaliphiles

Alkaliphiles microorganisms that have pH optima between 8.0 and 11. Vibrio cholerae, the pathogenic agent of cholera, grows best at the slightly basic pH of 8.0; it can survive pH values of 11.0 but is inactivated by the acid of the stomach. When it comes to survival at high pH, the bright pink halophilic archaeon Natronobacterium, found in the soda lakes of the African Rift Valley, may hold the record at a pH of 10.5. Extreme alkaliphiles have adapted to their harsh environment through various evolutionary modifications. Alkaliphilic archaea have diether lipid membranes. The ether linkage is more resistant to chemical or thermal degradation compared to the ester-linked phospholipids. Given the paucity of protons in alkaline environments, maintaining a proton motive force is probably the most pressing challenge for alkaliphiles. One of the adaptations of alkaliphilic halophilic bacteria and archaea in soda lakes and other highly salty environments is the evolution of coupled transporters and flagella that exploit sodium motive force, thus conserving the PMF for oxidative and photophosphorylation by the ATP synthase. The cell surface of alkaliphiles has a high concentration of acidic (i.e. negatively charged) molecules and it has been suggested this acts as a "proton sponge", allowing a more rapid lateral diffusion of protons from the ETS, to the ATP synthase, compared to the rate of diffusion into the surrounding waters. Finally, alkaliphiles may use Na^+/H^+ antiport to create a sodium motive force. For example, the alkaliphile *Bacillus firmus* derives the energy for transport reactions and motility from SMF rather than a proton motive force. As with the acidophiles, the genes for secreted proteins of alkaliphiles have evolved to give enzymes that resist deprotonation/denaturation and chemical degradation at the high pH of their environment. These enzymes are also of interest to biotechnology companies. In fact, laundry detergents, which are alkaline in nature, contain alkaliphilic lipases and proteases to improve their stain-removing abilities.

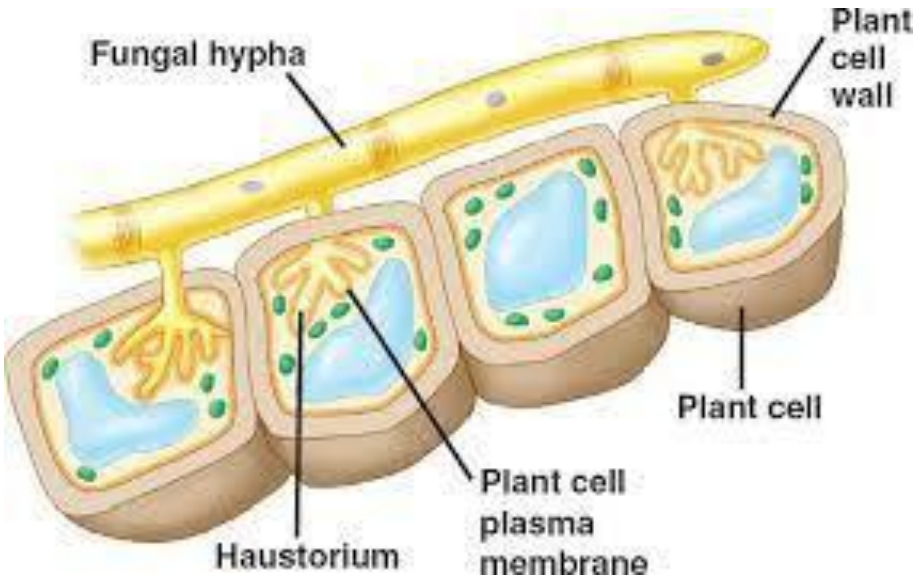
Fungal nutrition

Fungi get their nutrition by absorbing organic compounds from the environment. Fungi are heterotrophic: they rely solely on carbon obtained from other organisms for their metabolism and nutrition. Fungi have evolved in a way that allows many of them to use a large variety of organic substrates for growth, including simple compounds such as nitrate, ammonia, acetate, or ethanol. Their mode of nutrition defines the role of fungi in their environment.

Fungi obtain nutrients in three different ways:

1- They decompose dead organic matter. A saprotroph is an organism that obtains its nutrients from non-living organic matter, usually dead and decaying plant or animal matter, by absorbing soluble organic compounds. Saprotrophic fungi play very important roles as recyclers in ecosystem energy flow and biogeochemical cycles. Saprophytic fungi, such as shiitake (*Lentinula edodes*) and oyster mushrooms (*Pleurotus ostreatus*), decompose dead plant and animal tissue by releasing enzymes from hyphal tips. In this way they recycle organic materials back into the surrounding environment. Because of these abilities, fungi are the primary decomposers in forests.

2- They feed on living hosts. As parasites, fungi live in or on other organisms and get their nutrients from their host. Parasitic fungi use enzymes to break down living tissue, which may cause illness in the host. Disease-causing fungi are parasitic. Recall that parasitism is a type of symbiotic relationship between organisms of different species in which one, the parasite, benefits from a close association with the other, the host, which is harmed.



3- They live mutualistically with other organisms. Mutualistic fungi live harmless with other living organisms. The mutualism is an interaction between individuals of two different species, in which both individuals benefit.

Both parasitism and mutualism are classified as symbiotic relationships, but they are discussed separately here because of the different effect on the host.

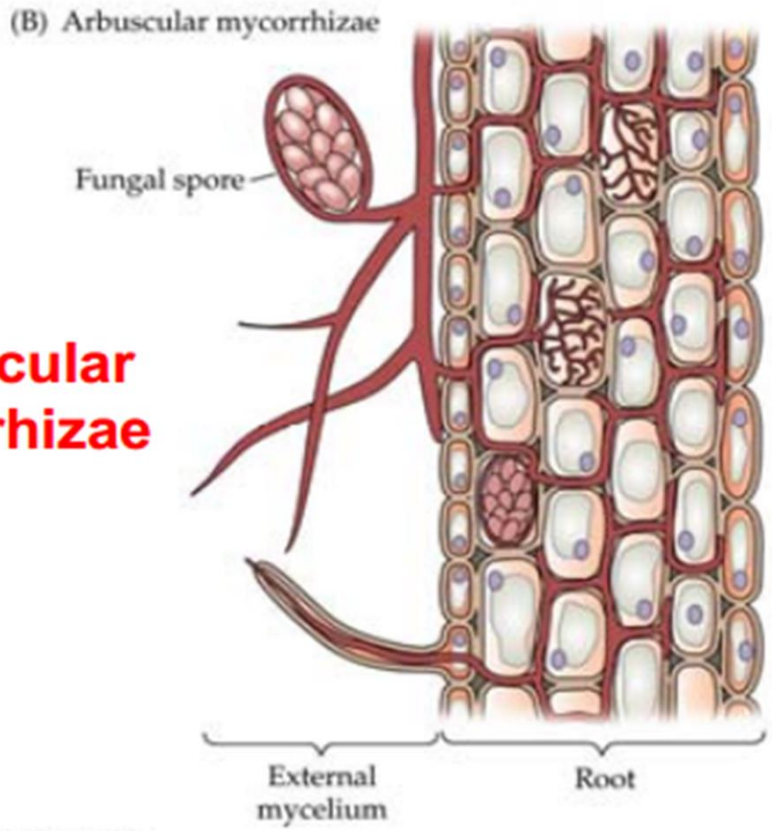
Fungal hyphae are adapted to efficient absorption of nutrients from their environments, because hyphae have high surface area-to-volume ratios. These adaptations are also complemented by the release of hydrolytic enzymes that break down large organic molecules such as polysaccharides, proteins, and lipids into smaller molecules. These molecules are then absorbed as nutrients into the fungal cells. One enzyme that is secreted by fungi is cellulase, which breaks down the polysaccharide cellulose. Cellulose is a major component of plant cell walls. In some cases, fungi have developed specialized structures for nutrient uptake from living hosts, which penetrate into the host cells for nutrient uptake by the fungus.

Fungi absorb nutrients from the environment through mycelia.

Mycorrhiza

A mycorrhiza (Greek for "fungus roots") is a symbiotic association between a fungus and the roots of a plant. In a mycorrhizal association, the fungus may colonize the roots of a host plant by either growing directly into the root cells, or by growing around the root cells. This association provides the fungus with relatively constant and direct access to glucose, which the plant produces by photosynthesis. The mycelia of the fungi increase the surface area of the plant's root system. The larger surface area improves water and mineral nutrient absorption from the soil.

Arbuscular mycorrhizae

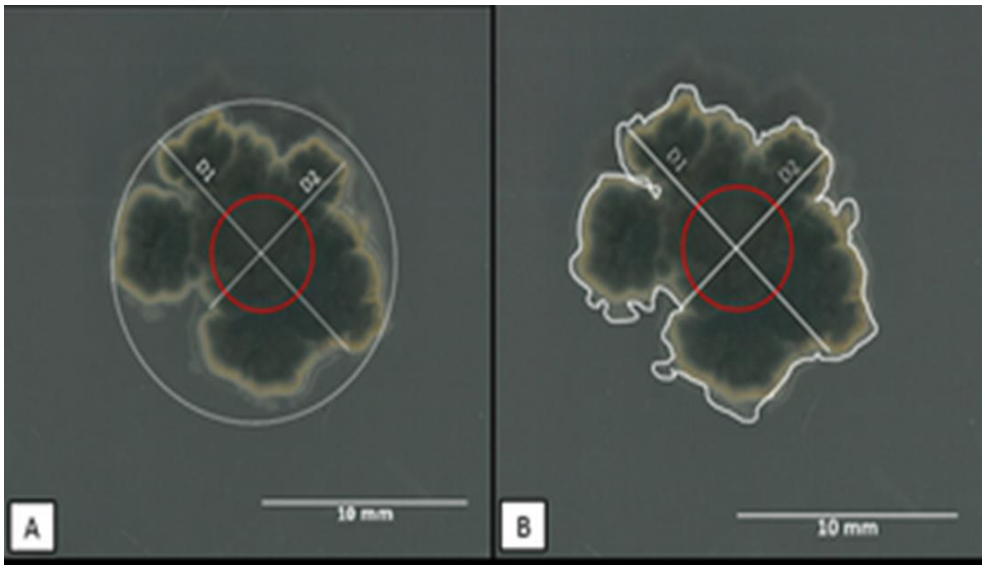


Measuring of fungal growth

The following points highlight the two methods used for measuring the growth in fungi. These methods are: 1. Linear Method (Agar Plate). 2. Mycelial Dry Weight.

1. Linear Method (Agar Plate)

After the fungal inoculum kept in the center of the agar plate, the radial growth of fungal colony can be measured and the rate of growth can be measured each 24 hours.



- Average of colony growth (diameter) = $\frac{D1+D2}{2}$

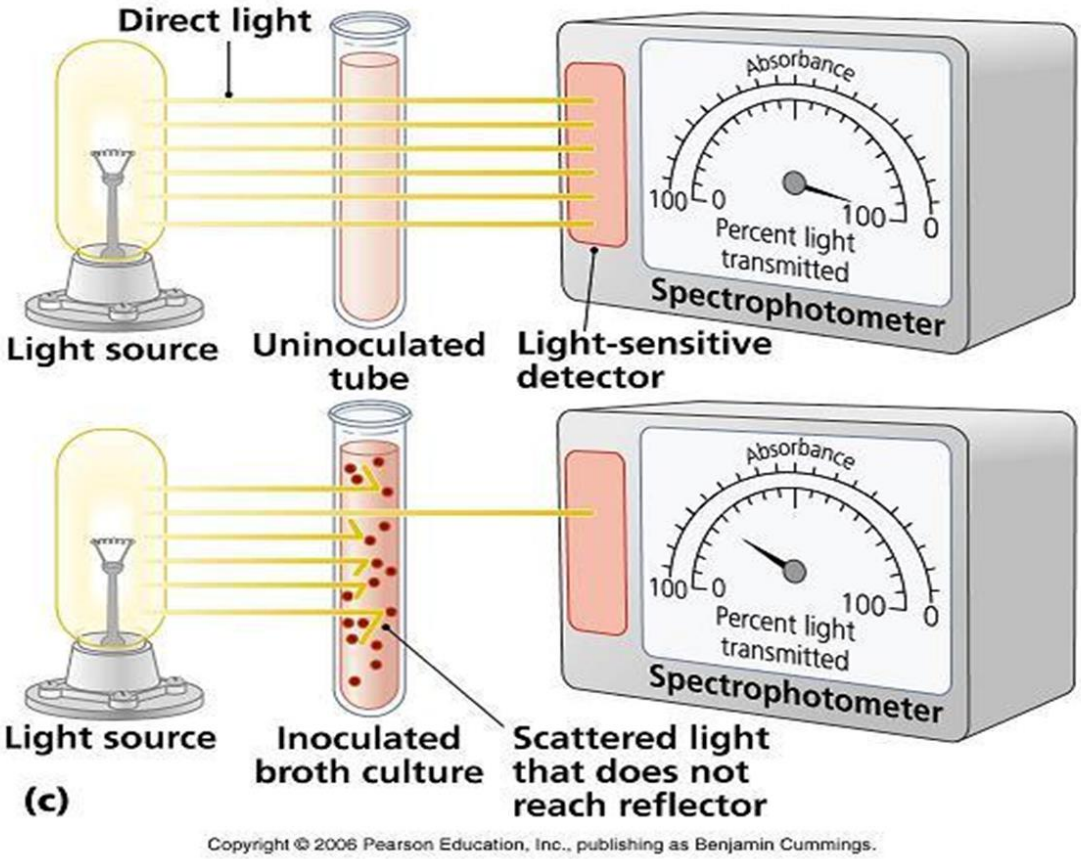
- Percentage of colony growth = $\frac{D1+D2}{2} \times 100$

2. Mycelial Dry Weight

On liquid medium (both stationary and aerated agitated cultures) the mycelial growth can be measured as dry weight. After inoculation of cultures, the cultures must be incubated at a suitable temperature and then the mycelial growth can be determined after filtration and drying of mycelia.

3- Spectrophotometric method

This method is used to measure the growth of unicellular organisms such as yeast and bacterial species using spectrophotometric analysis. Significant variations are found in the growth patterns of budding and fission of yeast. The spectrophotometer absorbance depends on the turbidity in the liquid medium due to the growth rate of yeast.



Carbon metabolism

Metabolism: The entire spectrum of living chemical reactions, occurring in living system. Metabolism is broadly classified into two:

Anabolism: biosynthetic reactions involving in the formation of complex molecules from simple precursors.

Catabolism: degradation processes concerned with the breakdown of complex molecules to simpler ones with release of energy.

Respiration

Glycolysis (Degradation of glucose to pyruvate)

The major function of carbohydrates in metabolism is as a fuel to be oxidized and provide energy for other metabolic processes. The carbohydrate is utilized by cells mainly as glucose. The three principal monosaccharides resulting from digestive processes are glucose, fructose, and galactose. Much of the glucose is derived from starch which accounts for over half of the fuel in the diets of most humans. Glucose is also produced from other dietary components by the liver and, to a lesser extent, by the kidneys. Fructose results in a large intake of sucrose while galactose is produced when lactose is the principal carbohydrate of the diet. Both fructose and galactose are easily converted to glucose by the liver. It is thus apparent that glucose is the major fuel of most organisms and that it can be quickly metabolized from glycogen stores when there arises a sudden need for energy. Pentose sugars such as arabinose, ribose and xylose may be present in the diet. But their fate after absorption is, however, obscure.

Glycolysis is the sequence of 10 enzyme-catalyzed reactions that convert glucose into pyruvate with the simultaneous production of ATP. The glycolytic sequence of reactions differs from one species to the other only in the mechanism of its regulation and in the subsequent metabolic fate of the pyruvate formed. In aerobic organisms, glycolysis is the prelude to the citric acid cycle and the electron transport chain which together harvest most of the energy contained in glucose. In fact, glycolysis is the central pathway of glucose catabolism. Glycolysis takes

place outside the mitochondria in the cytoplasm. It is frequently referred to as Embden-Meyerhof-Pathway (EMP pathway), in the honors of these pioneer workers in the field, and still represents one of the greatest achievements in the field of biochemistry. (https://www.youtube.com/watch?v=8qij1m7XUhk), (https://www.youtube.com/watch?v=UBudWWUqAmc).

Glycolysis is the metabolic process that serves as the foundation for both aerobic and anaerobic cellular respiration. In glycolysis, glucose is converted into pyruvate. Glucose is a six-membered ring molecule found in the blood and is usually a result of the breakdown of carbohydrates into sugars. It enters cells through specific transporter proteins that move it from outside the cell into the cell's cytosol. All of the glycolytic enzymes are found in the cytosol. The overall reaction of glycolysis which occurs in the cytoplasm is represented simply as:

$C_6H_{12}O_6$ + 2 NAD + 2 ADP + 2 P ——> 2 Pyruvic acid + 2 ATP + 2 NADH + 2 H^+

Step 1

The first step in glycolysis is the conversion of D-glucose into glucose 6-phosphate. The enzyme that catalyzes this reaction is hexokinase. The glucose ring is phosphorylated. Phosphorylation is the process of adding a phosphate group to a molecule derived from ATP. As a result, at this point in glycolysis, 1 molecule of ATP has been consumed. The reaction occurs with the help of the enzyme hexokinase, an enzyme that catalyzes the phosphorylation of many six-membered glucose-like ring structures. Atomic magnesium (Mg) is also involved to help shield the negative charges from the phosphate groups on the ATP molecule. The result of this phosphorylation is a molecule called glucose 6-phosphate (G6P), because the 6′ carbon of the glucose acquires the phosphate group.

Step 2

The second reaction of glycolysis is the rearrangement of glucose 6-phosphate (G6P) into fructose 6-phosphate (F6P) by glucose phosphate isomerase (Phosphoglucose Isomerase). The second step of glycolysis involves the conversion of glucose-6-phosphate to fructose-6-phosphate (F6P). This reaction occurs with the help of the enzyme phosphoglucose isomerase (PI). The reaction involves the rearrangement of the carbon-oxygen bond to transform the six-membered ring into a five-membered ring. To rearrangement takes place when the six-membered ring opens and then closes in such a way that the first carbon becomes now external to the ring.

Step 3

Phosphofructokinase, with magnesium as a cofactor, changes fructose 6-phosphate into fructose 1,6-bisphosphate. In the third step of glycolysis, fructose 6-phosphate is converted to fructose 1,6-bisphosphate (FBP). Similar to the reaction that occurs in step 1 of glycolysis, a second molecule of ATP provides the phosphate group that is added on to the F6P molecule. The enzyme that catalyzes this reaction is phosphofructokinase (PFK). As in step 1, a magnesium atom is involved to help shield negative charges.

Step 4

The enzyme Aldolase splits fructose 1,6-bisphosphate into two sugars that are isomers of each other. These two sugars are dihydroxyacetone phosphate (DHAP) and glyceraldehyde 3-phosphate (GAP). This step utilizes the enzyme aldolase, which catalyzes the cleavage of FBP to yield two 3-carbon molecules. One of these molecules is called glyceraldehyde-3-phosphate (GAP) and the other is called dihydroxyacetone phosphate (DHAP).

Step 5

The enzyme triosephosphate isomerase rapidly inter-converts the molecules dihydroxyacetone phosphate (DHAP) and glyceraldehyde 3-phosphate (GAP). Glyceraldehyde phosphate is removed / used in next step of Glycolysis. GAP is

the only molecule that continues in the glycolytic pathway. As a result, all of the DHAP molecules produced are further acted on by the enzyme Triosephosphate isomerase (TIM), which reorganizes the DHAP into GAP so it can continue in glycolysis. At this point in the glycolytic pathway, we have two 3-carbon molecules.

Step 6

Glyceraldehyde 3-phosphate dehydrogenase (GAPDH) dehydrogenates and adds an inorganic phosphate to glyceraldehyde 3-phosphate, producing 1,3-bisphosphoglycerate. In this step, two main events take place: 1- glyceraldehyde 3-phosphate is oxidized by the coenzyme nicotinamide adenine dinucleotide (NAD); 2- the molecule is phosphorylated by the addition of a free phosphate group. The enzyme that catalyzes this reaction is glyceraldehyde-3-phosphate dehydrogenase (GAPDH). The enzyme GAPDH contains appropriate structures and holds the molecule in a conformation such that it allows the NAD molecule to pull a hydrogen off the GAP, converting the NAD to NADH. The phosphate group then attacks the GAP molecule and releases it from the enzyme to yield 1,3 biphosphoglycerate, NADH, and a hydrogen atom.

Step 7

Phosphoglycerate kinase transfers a phosphate group from 1,3-biphosphoglycerate to ADP to form ATP and 3-phosphoglycerate. In this step, 1,3 biphosphoglycerate is converted to 3-phosphoglycerate by the enzyme phosphoglycerate kinase (PGK). This reaction involves the loss of a phosphate group from the starting material. The phosphate is transferred to a molecule of ADP that yields our first molecule of ATP. Since we actually have two molecules of 1,3 biphosphoglycerate (because there were two 3-carbon products from stage 1 of glycolysis), we actually synthesize two molecules of ATP at this step. With this synthesis of ATP, we have cancelled the first two molecules of ATP that we used, leaving us with a net of 0 ATP molecules up to this stage of glycolysis.

Again, we see that an atom of magnesium is involved to shield the negative charges on the phosphate groups of the ATP molecule.

Step 8

The enzyme phosphoglycero mutase relocates the P from 3-phosphoglycerate from the 3rd carbon to the 2nd carbon to form 2-phosphoglycerate. This step involves a simple rearrangement of the position of the phosphate group on the 3 phosphoglycerate molecule, making it 2-phosphoglycerate. The molecule responsible for catalyzing this reaction is called phosphoglycerate mutase (PGM). A mutase is an enzyme that catalyzes the transfer of a functional group from one position on a molecule to another. The reaction mechanism proceeds by first adding an additional phosphate group to the 2′ position of the 3 phosphoglycerate. The enzyme then removes the phosphate from the 3′ position leaving just the 2′ phosphate, and thus yielding 2 phsophoglycerate. In this way, the enzyme is also restored to its original, phosphorylated state.

Step 9

The enzyme enolase removes a molecule of water from 2-phosphoglycerate to form phosphoenolpyruvate (PEP). This step involves the conversion of 2 phosphoglycerate to phosphoenolpyruvate (PEP). The reaction is catalyzed by the enzyme enolase. Enolase works by removing a water group, or dehydrating the 2 phosphoglycerate.

Step 10

The enzyme pyruvate kinase transfers a P from phosphoenolpyruvate (PEP) to ADP to form pyruvic acid and ATP Result in step 10. The final step of glycolysis converts phosphoenolpyruvate into pyruvate with the help of the enzyme pyruvate kinase. As the enzyme's name suggests, this reaction involves the transfer of a phosphate group. The phosphate group attached to the 2′ carbon of the PEP is transferred to a molecule of ADP, yielding ATP. Again, since there are two molecules of PEP, here we actually generate 2 ATP molecules.

Steps 1 and 3 = – 2 ATP, Steps 7 and 10 = + 4 ATP, Therefore Net ATP produced = 2.

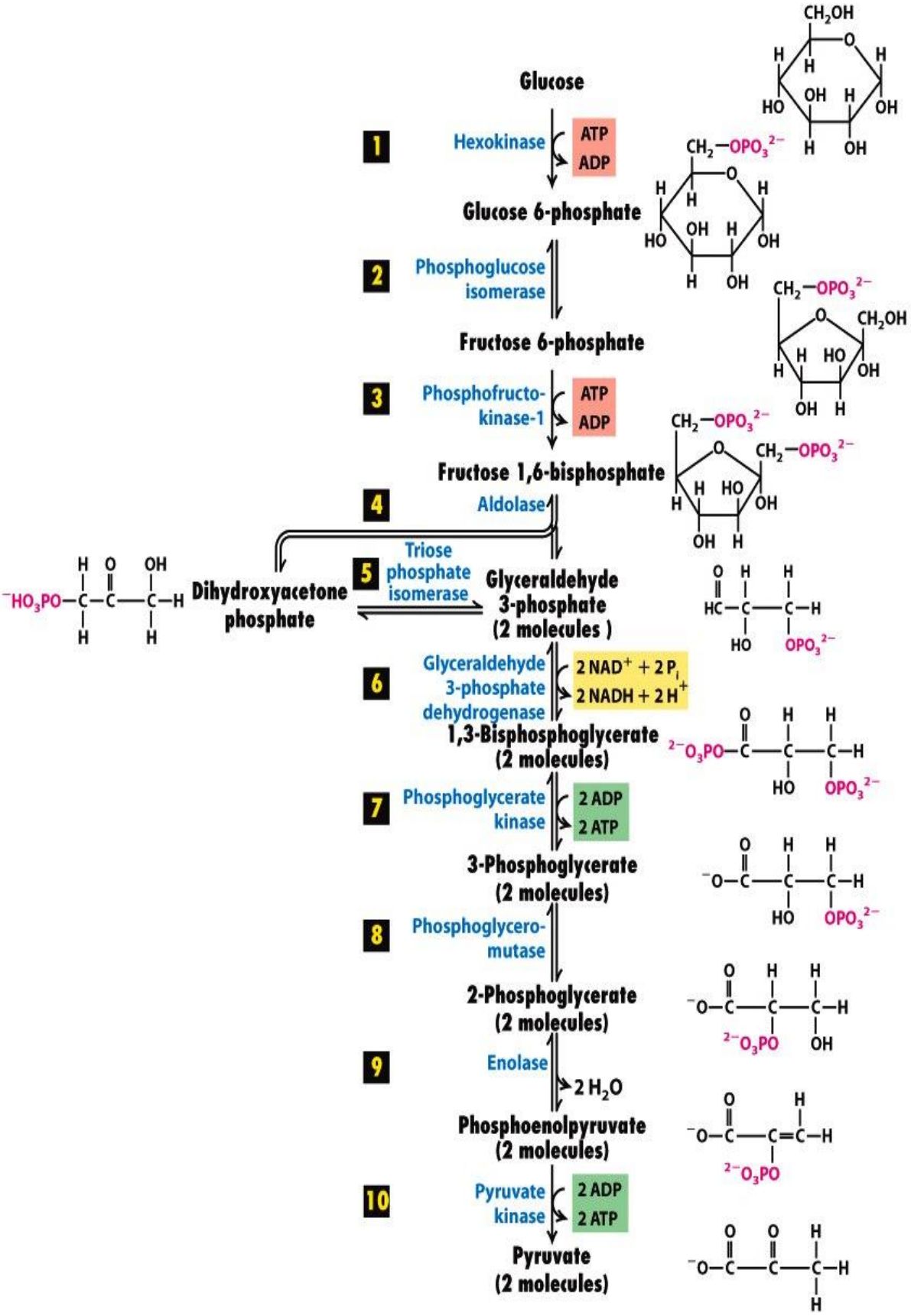


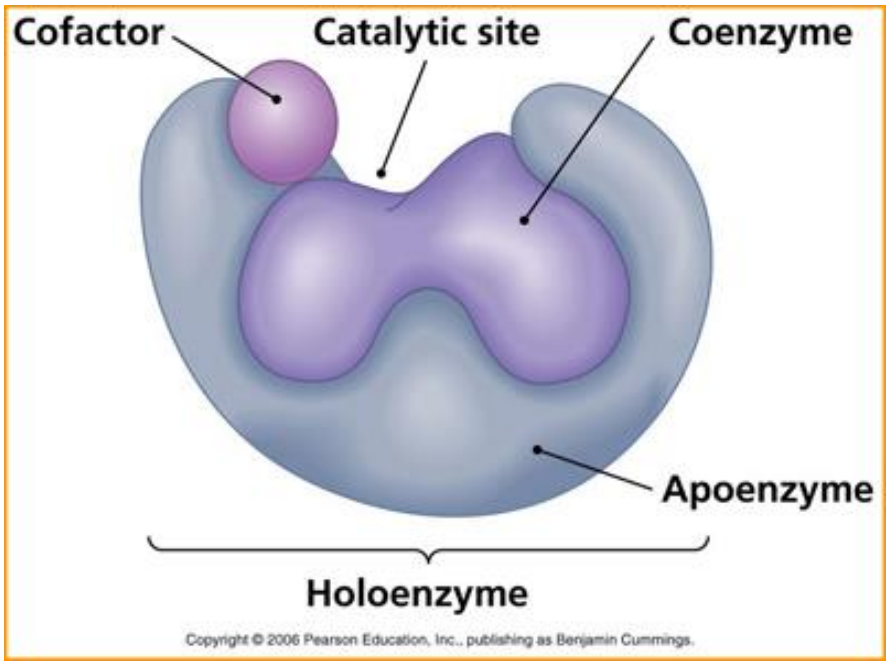
Figure 12-3
Molecular Cell Biology, Sixth Edition

Cofactors

The cofactors are non-protein compounds that assists with a biological chemical reaction. Cofactors may be metal ions, organic compounds, or other chemicals that have helpful properties not usually found in amino acids. Some cofactors can be made inside the cell, such as ATP, while others must be consumed in food. Minerals, for example, come from the environment, and cannot be made from scratch by any living cell. The organic compounds we refer to as "vitamins" are cofactors that our own bodies cannot make, so we must consume them from food in order for our cells to be able to perform essential life functions.

At the biochemical level, cofactors are important in understanding how biological reactions proceed. The presence or absence of cofactors may determine how quickly reactions proceed from their reactant to their product.

- **Cofactor**: A substance, especially a coenzyme or a metal, that must be present for an enzyme to function.
- **Enzymes**: Enzymes are large biological molecules responsible for the thousands of chemical interconversions that sustain life. They are highly selective catalysts, greatly accelerating both the rate and specificity of metabolic reactions, from the digestion of food to the synthesis of DNA.
- **Reaction**: A chemical reaction is a process that leads to the transformation of one set of chemical substances to another. Classically, chemical reactions encompass changes that strictly involve the motion of electrons in the forming and breaking of chemical bonds between atoms, and can often be described by a chemical equation.
- **Apoenzyme**: an inactive haloenzyme lacking a cofactor.


Cofactor
Catalytic site
Coenzyme
Apoenzyme
Holoenzyme
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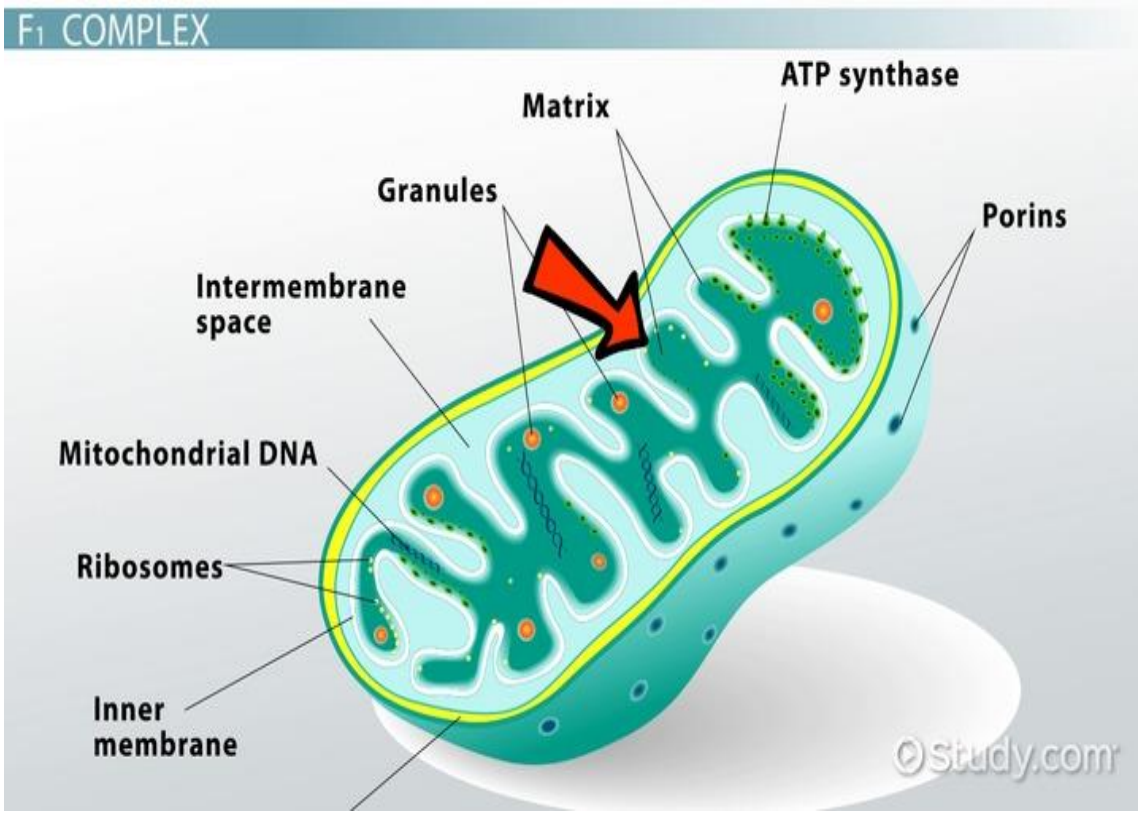
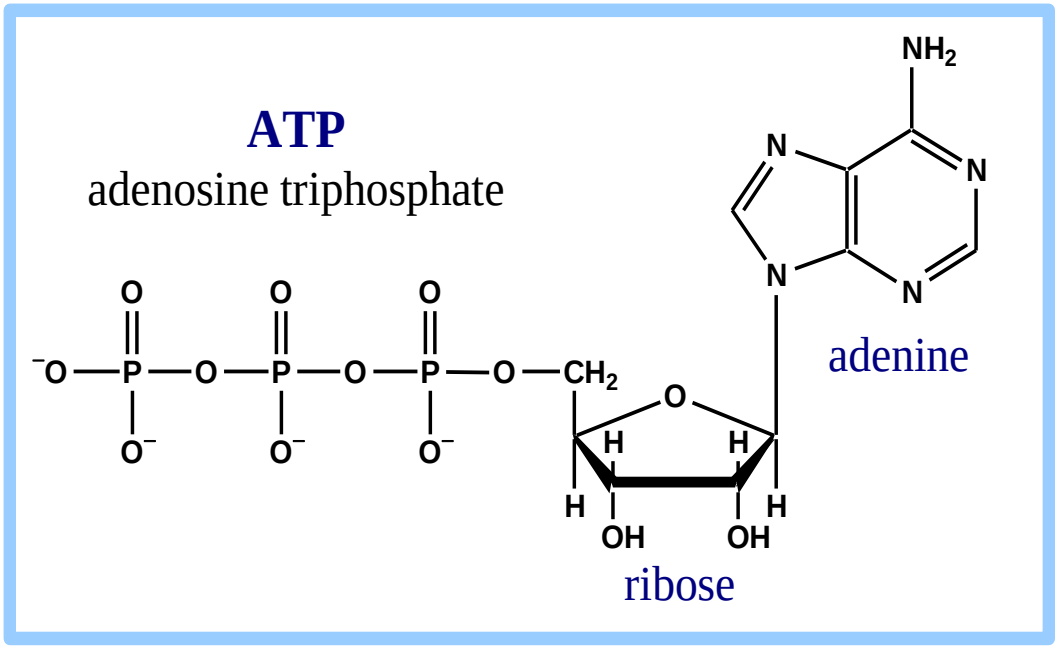
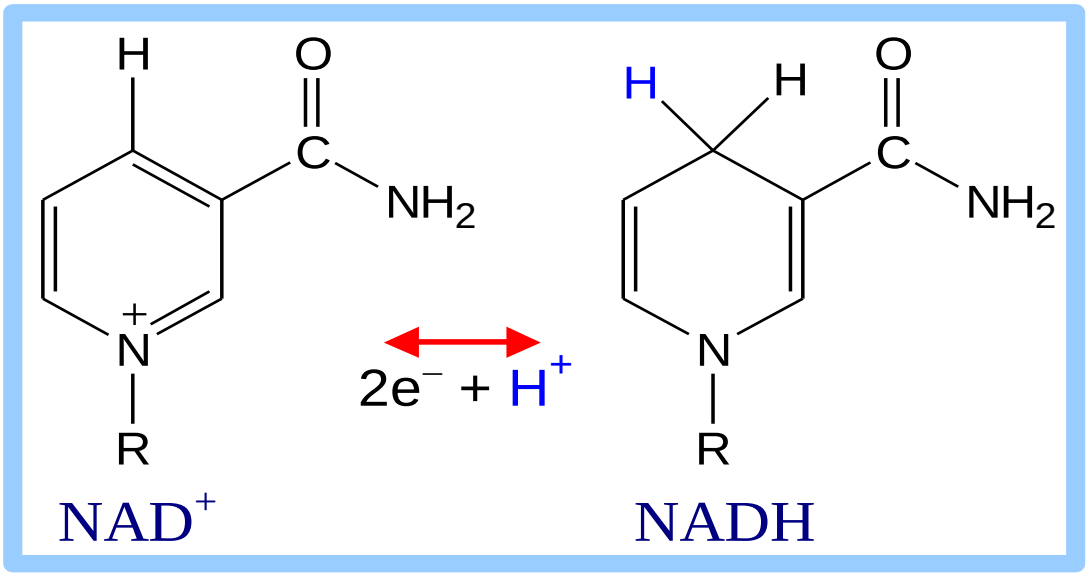

F1 COMPLEX
ATP synthase
Matrix
Granules
Porins
Intermembrane space
Mitochondrial DNA
Ribosomes
Inner membrane
Study.com



Adenosine triphosphate (ATP)



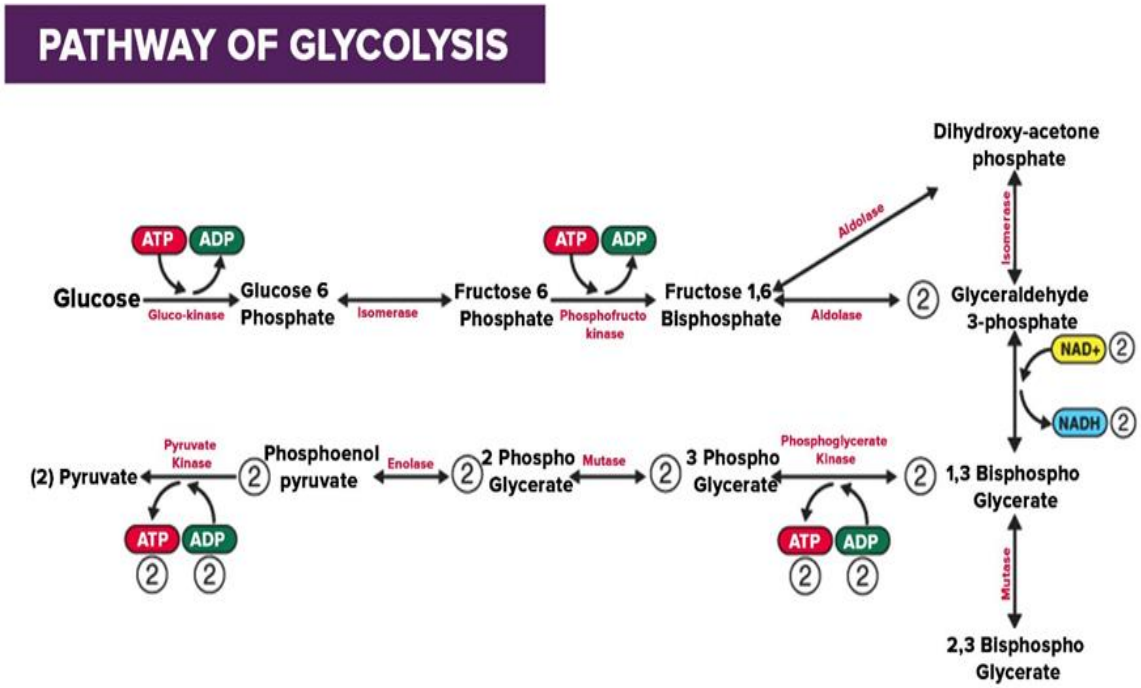
Nicotinamide adenine dinucleotide (NAD)

Nicotinamide adenine dinucleotide (NAD+) and flavin adenine dinucleotide (FAD+) are two cofactors that are involved in cellular respiration. They are responsible for accepting "high energy" electrons and carrying them ultimately to the electron transport chain where they are used to synthesize ATP molecules. Therefore, although they themselves are not a direct source of energy, they are

used to form ATP energy molecules that are used by the cell. When these electron-carrier molecules accept the electrons, they are reduced into NADH and $FADH_2$.

ATP and NADH produced by glycolysis

It is the process of breaking down glucose to create energy. Glycolysis generates 2 ATP and 2 NADH, for a total of 8 ATP molecules.



Krebs cycle (Citric acid cycle)

The German chemist Hans Adolf Krebs discovery this cycle in 1937 marked a milestone in biochemistry. Krebs received the Nobel Prize for Physiology or Medicine in 1953 for this contribution to the study of intermediary metabolism in the oxidative breakdown of carbohydrates. Krebs and his coauthor William Arthur Johnson published their findings "The role of citric acid in intermediate metabolism in animal tissues" in Enzymologia after being rejected by Nature. That original publication was followed by many more.

Krebs or Citric acid cycle, also known as the tricarboxylic acid (TCA) cycle, is the main source of energy for cells and an important part of aerobic respiration. The cycle harnesses the available chemical energy of acetyl coenzyme A (acetyl-CoA) into the reducing power of nicotinamide adenine dinucleotide (NADH). The TCA cycle is part of the larger glucose metabolism whereby glucose is oxidized to form pyruvate, which is then oxidized and enters the TCA cycle as acetyl-CoA. Half of the intermediates on which the cycle depends are also the origin of pathways leading to important compounds such as fatty acids, amino acids, or porphyrins. If any of these intermediates are thus diverted, the integrity of the cycle is broken and the cycle no longer functions. Production of essential energy can only be resumed if the diverted intermediate or a subsequent intermediate that leads to oxaloacetate can be replenished by refilling reactions.

Krebs cycle intermediates (precursors)

These intermediates are numbered on the diagram below as Citrate, Isocitrate, Oxoglutarate, Succinyl-CoA, Succinate, Fumarate, Malate, Oxaloacetate (Oxaloacetic acid).

Krebs cycle steps

It is an eight steps process. Krebs cycle or TCA cycle takes place in the matrix of mitochondria under aerobic condition.

Step 1: The first step is the condensation of acetyl CoA with 4-carbon compound oxaloacetate to form 6C citrate, coenzyme A is released. The reaction is catalyzed by citrate synthase.

Step 2: Citrate is converted to its isomer, isocitrate. The enzyme aconitase catalyzes this reaction.

Step 3: Isocitrate undergoes dehydrogenation and decarboxylation to form 5C **α**-ketoglutarate. A molecular form of CO2 is released. Isocitrate dehydrogenase catalyzes the reaction. It is an NAD^+ dependent enzyme. NAD^+ is converted to NADH.

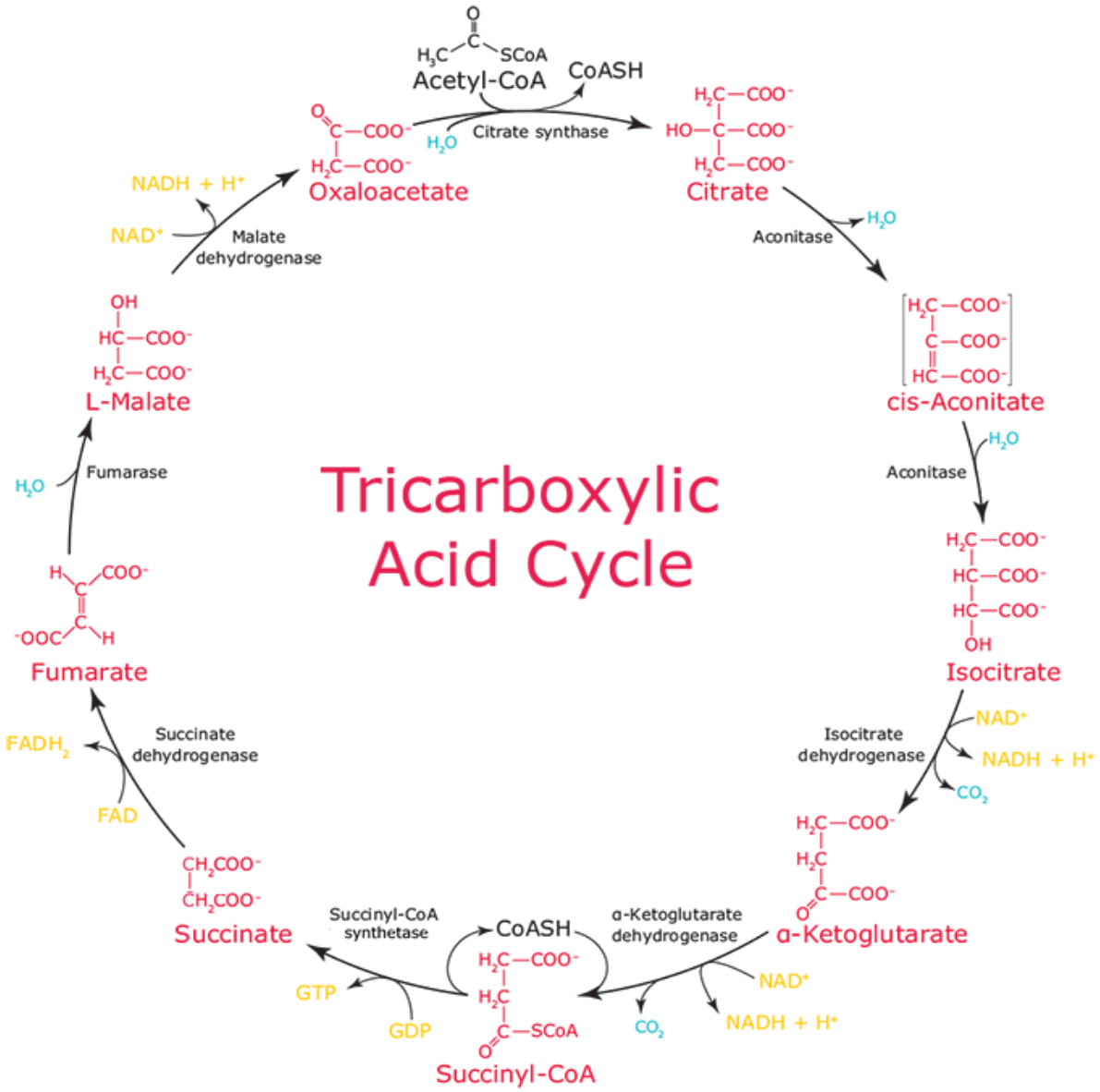
Step 4: **α**-ketoglutarate undergoes oxidative decarboxylation to form succinyl CoA, a 4C compound. The reaction is catalyzed by the **α**-ketoglutarate dehydrogenase enzyme complex. One molecule of CO_2 is released and NAD^+ is converted to NADH.

Step 5: Succinyl CoA forms succinate. The enzyme succinyl CoA synthetase catalyzes the reaction. This is coupled with substrate-level phosphorylation of GDP to get GTP. GTP transfers its phosphate to ADP forming ATP.

Step 6: Succinate is oxidized by the enzyme succinate dehydrogenase to fumarate. In the process, FAD is converted to $FADH_2$.

Step 7: Fumarate gets converted to malate by the addition of one H_2O. The enzyme catalyzing this reaction is fumarase.

Step 8: Malate is dehydrogenated to form oxaloacetate, which combines with another molecule of acetyl CoA and starts the new cycle. Hydrogens removed, get transferred to NAD^+ forming NADH. Malate dehydrogenase catalyzses the reaction. (https://www.youtube.com/watch?v=ubzw64PQPqM).



Summary of Krebs cycle

Location: Krebs cycle occurs in the mitochondrial matrix.

Krebs cycle reactants: Acetyl CoA, which is produced from the end product of glycolysis, i.e. pyruvate and it condenses with 4 carbon oxaloacetate, which is generated back in the Krebs cycle.

Krebs cycle products

Each citric acid cycle forms the following products:

2 molecules of CO_2 are released. Removal of CO_2 or decarboxylation of citric acid takes place at two places: In the conversion of isocitrate (6C) to **α**-ketoglutarate (5C). In the conversion of **α**-ketoglutarate (5C) to succinyl CoA (4C). 1 ATP is produced in the conversion of succinyl CoA to succinate, 3 NAD^+ are reduced to NADH and 1 FAD^+ is converted to $FADH_2$ in the following reactions:

Isocitrate to **α**-ketoglutarate → NADH

α-ketoglutarate to succinyl CoA → NADH

Succinate to fumarate → $FADH_2$

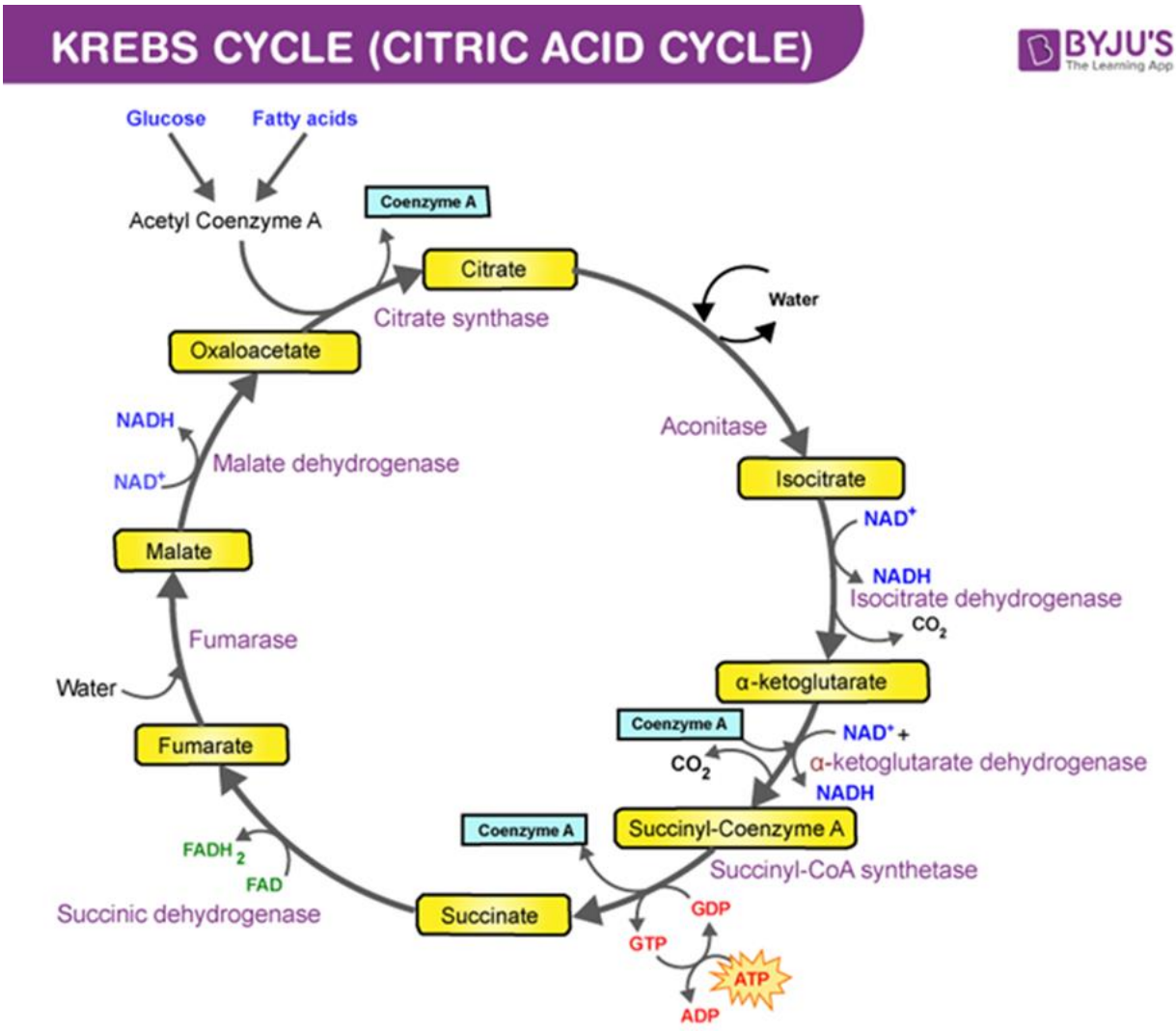
Malate to Oxaloacetate → NADH

Note that 2 molecules of Acetyl CoA are produced from oxidative decarboxylation of 2 pyruvates so two cycles are required per glucose molecule. To summarize, for complete oxidation of a glucose molecule, Krebs cycle yields 4 CO_2, 6 NADH, 2 $FADH_2$ and 2 ATPs. Each molecule of NADH can form 2-3 ATPs and each $FADH_2$ gives 2 ATPs on oxidation in the electron transport chain. It is a series of events in living organisms in which acetic acid or acetyl equivalent oxidation produces energy for storage in phosphate bonds (as in ATP).

The Krebs cycle yields three NADH molecules (two cycles) and 18 ATP molecules. In two cycles, four $FADH_2$ molecules are generated, yielding four ATP molecules. Two GTP molecules are created in two cycles, resulting in the release of two ATP molecules.

TCA cycle applications

These TCA-related metabolic applications are commonly studied using stable isotope-labeled compounds and mass spectrometry: Lipid metabolism, Amino acid metabolism, Protein metabolism (Turnover), Glucose metabolism, Energy expenditure, Metabolomics.



Significance of Krebs cycle

Krebs cycle is the final pathway of oxidation of glucose, fats and amino acids. Many organisms are dependent on nutrients other than glucose as an energy source. Amino acids (metabolic product of proteins) are deaminated and get converted to pyruvate and other intermediates of the Krebs cycle. They enter the cycle and get metabolized e.g. alanine is converted to pyruvate, glutamate to **α**-ketoglutarate, aspartate to oxaloacetate on deamination.

Fatty acids undergo ***β***-oxidation to form acetyl CoA, which enters the Krebs cycle. It is the major source of ATP production in the cells. A large amount of energy is produced after complete oxidation of nutrients. It plays an important role in gluconeogenesis and lipogenesis and interconversion of amino acids.

Many intermediate compounds are used in the synthesis of amino acids, nucleotides, cytochromes and chlorophylls, etc. Vitamins play an important role in the citric acid cycle. Riboflavin, niacin, thiamin and pantothenic acid as a part of various enzymes cofactors (FAD, NAD) and coenzyme A.

Regulation of Krebs cycle depends on the supply of NAD^+ and utilization of ATP in physical and chemical work. The genetic defects of the Krebs cycle enzymes are associated with neural damage. As most of the biological processes occur in the liver to a significant extent, damage to liver cells has a lot of repercussions.

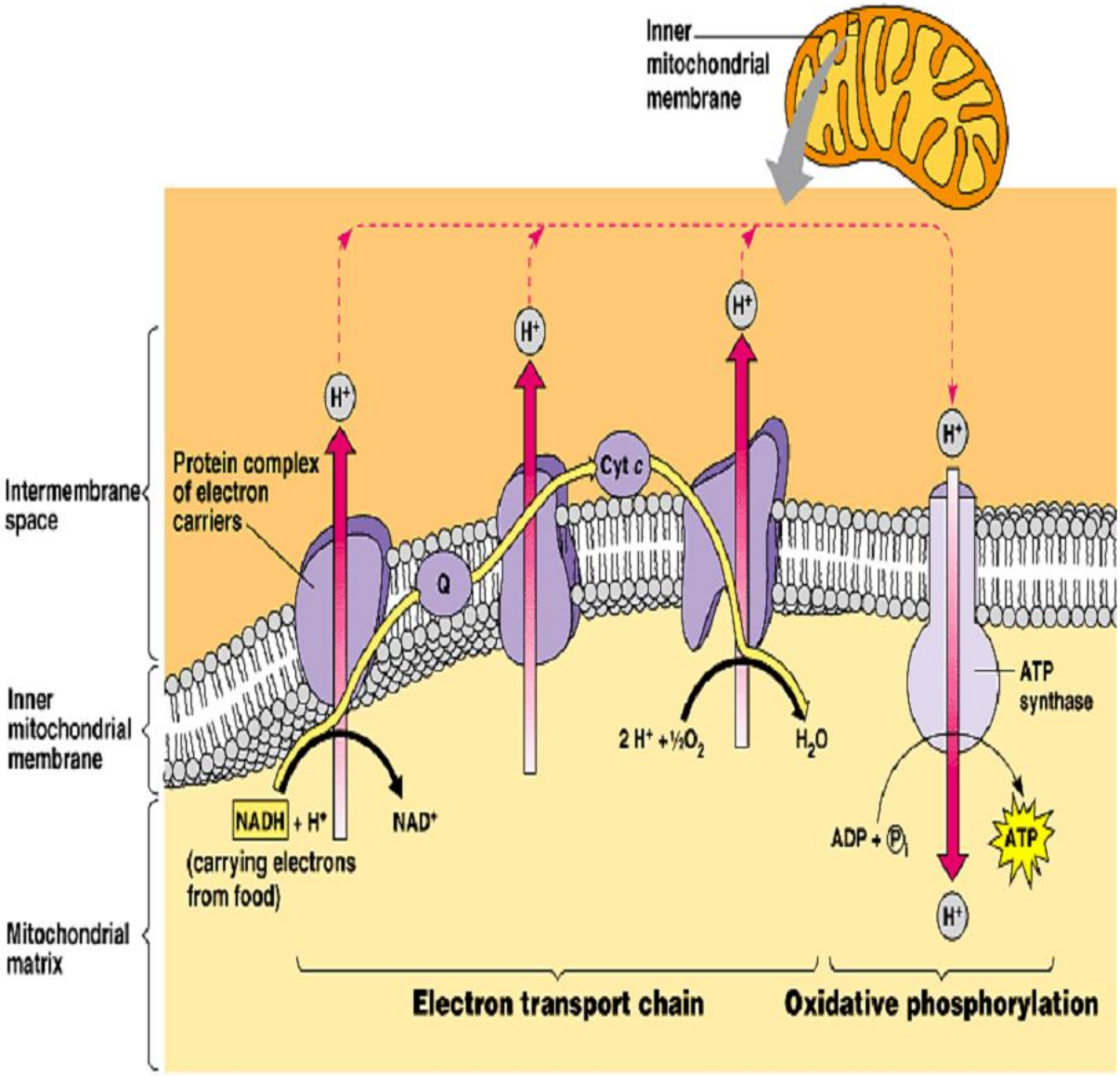
Hyperammonemia occurs in liver diseases and leads to convulsions and coma. This is due to reduced ATP generation as a result of the withdrawal of **α**-ketoglutarate and formation of glutamate, which forms glutamine.

Electron transport chain (Oxidative phosphorylation)

The electron transport chain is a series of four protein complexes that couple redox reactions, creating an electrochemical gradient that leads to the creation of ATP in a complete system named oxidative phosphorylation. It occurs in mitochondria in both cellular respiration and photosynthesis. In the former, the electrons come from breaking down organic molecules, and energy is released. In the latter, the electrons enter the chain after being excited by light, and the energy released is used to build carbohydrates.

Aerobic cellular respiration is made up of three parts: glycolysis, the citric acid (Krebs) cycle, and oxidative phosphorylation. In glycolysis, glucose metabolizes into two molecules of pyruvate, with an output of ATP and nicotinamide adenine dinucleotide (NADH). Each pyruvate oxidizes into acetyl CoA and an additional molecule of NADH and carbon dioxide (CO_2). The acetyl CoA is then used in the citric acid cycle, which is a chain of chemical reactions that produce CO_2, NADH, flavin adenine dinucleotide ($FADH_2$), and ATP. In the final step, the three NADH and one $FADH_2$ amassed from the previous steps are used in oxidative

phosphorylation, to make water and ATP. (https://www.youtube.com/watch?v=zJNx1DDqIVo).



Electron transport chain

It is the metabolic mechanism through which electrons move from one carrier to another. In two cycles, oxidative phosphorylation produces two NADH molecules while releasing six ATP molecules. All of the preceding events result in a net ATP gain of 38 molecules from a single glucose molecule.

Fermentation

Fermentation occurs in the absence of oxygen (anaerobic conditions), and in the presence of beneficial microorganisms (yeasts, molds, and bacteria) that obtain their energy through fermentation. If enough sugar is available, some yeast cells, such as *Saccharomyces cerevisiae*, prefer fermentation to aerobic respiration even when oxygen is abundant.

1. During the fermentation process, these beneficial microbes break down sugars and starches into alcohols and acids, making food more nutritious and preserving it so people can store it for longer periods of time without it spoiling.

2. Fermentation products provide enzymes necessary for digestion. This is important because humans are born with a finite number of enzymes, and they decrease with age. Fermented foods contain the enzymes required to break them down.

3. Fermentation also aids in pre-digestion. During the fermentation process, the microbes feed on sugars and starches, breaking down food before anyone's even consumed it.

Advantages of fermentation

Fermented foods are rich in probiotics, beneficial microorganisms that help maintain a healthy gut so it can extract nutrients from food.

1. Probiotics aid the immune system because the gut produces antibiotic, anti-tumor, anti-viral, and antifungal substances, and pathogens don't do well in the acidic environment fermented foods create.

2. Fermentation also helps neutralize anti-nutrients like phytic acid, which occurs in grains, nuts, seeds, and legumes and can cause mineral deficiencies. Phytates also make starches, proteins, and fats less digestible, so neutralizing them is extremely beneficial.

3. Fermentation can increase the vitamins and minerals in food and make them more available for absorption. Fermentation increases B and C vitamins and enhances folic acid, riboflavin, niacin, thiamin, and biotin. The probiotics,

enzymes, and lactic acid in fermented foods facilitate the absorption of these vitamins and minerals into the body.

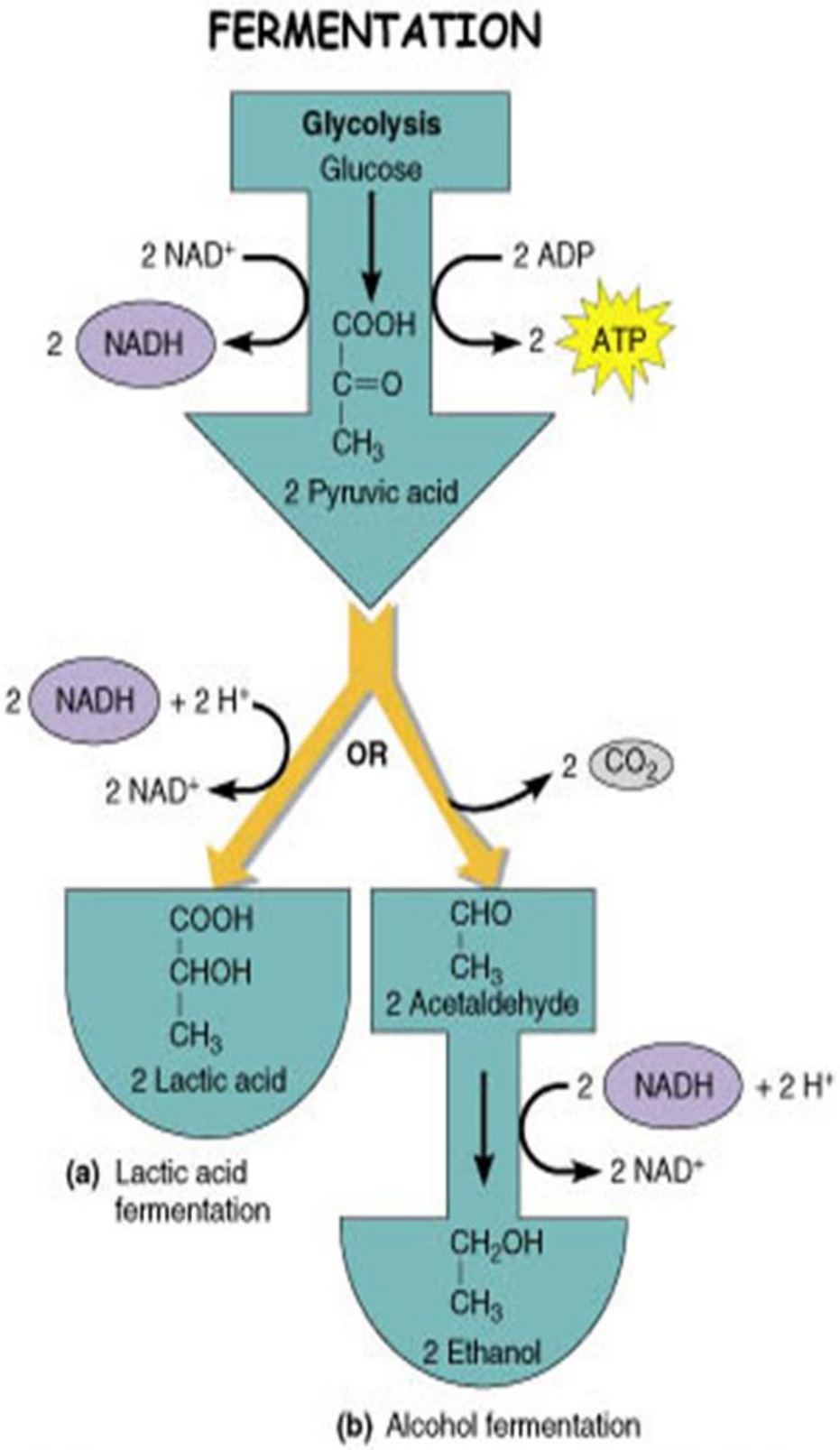
Types of fermentation

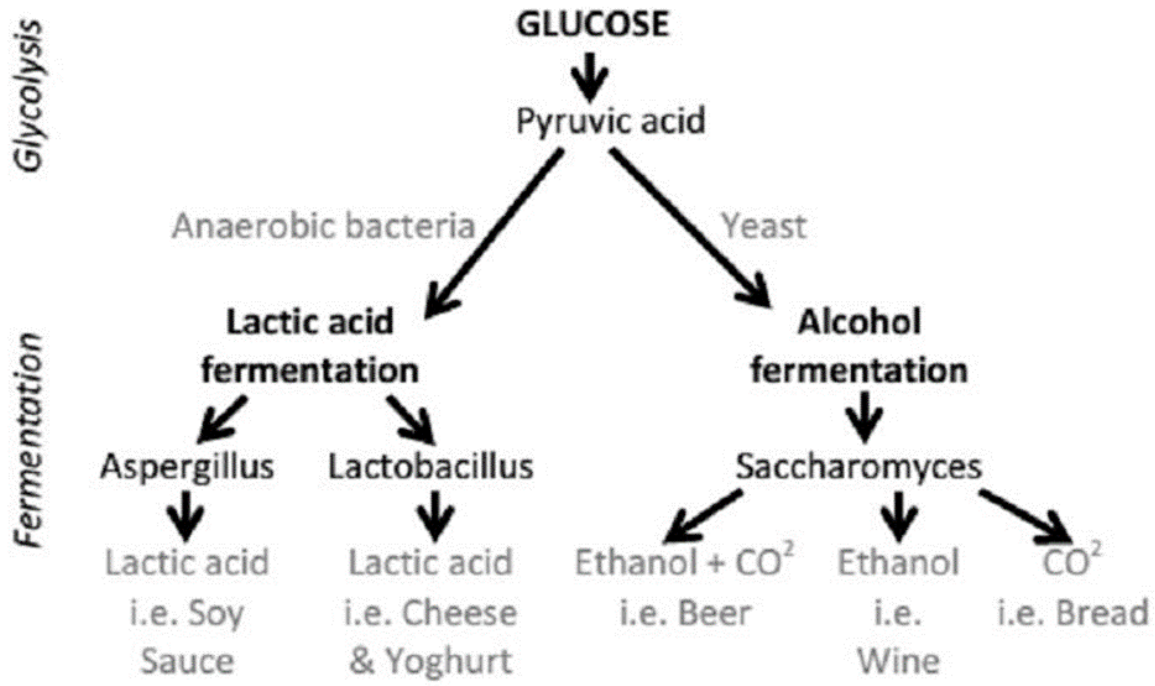
Microbes specialized at converting certain substances into others can produce a variety of foodstuffs and beverages. These are three distinct types of fermentation that people use.

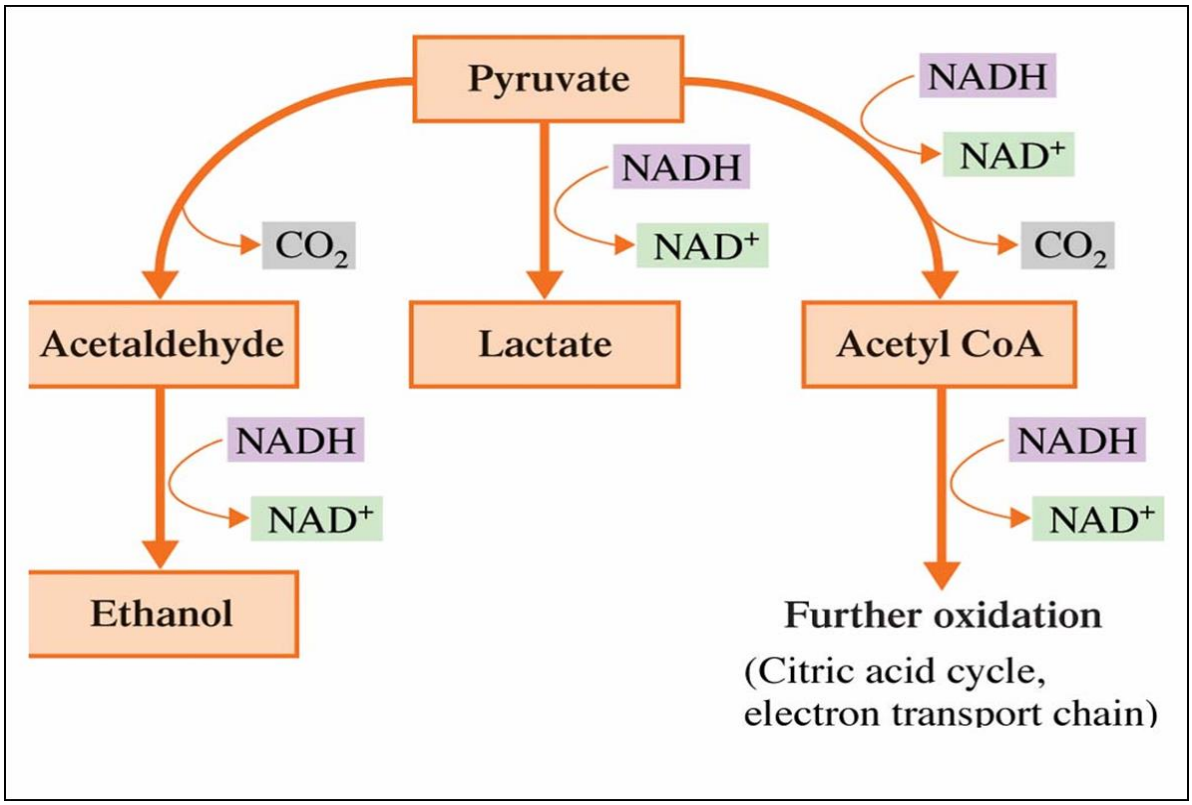
1. Lactic acid fermentation. Yeast strains and bacteria convert starches or sugars into lactic acid, requiring no heat in preparation. These anaerobic chemical reactions, pyruvic acid uses nicotinamide adenine dinucleotide+hydrogen (NADH) to form lactic acid and NAD^+ (Lactic acid fermentation also occurs in human muscle cells. During strenuous activity, muscles can expend adenosine triphosphate (ATP) faster than oxygen can be supplied to muscle cells, resulting in lactic acid buildup and sore muscles. In this scenario, glycolysis, which breaks down a glucose molecule into two pyruvate molecules and doesn't use oxygen, produces ATP). Lactic acid bacteria are vital to producing and preserving inexpensive, wholesome foods, which is especially important in feeding impoverished populations. This method makes sauerkraut, pickles, kimchi, yogurt, and sourdough bread.

2. Alcohol fermentation/Ethanol fermentation. Yeasts break pyruvate molecules—the output of the metabolism of glucose ($C_6H_{12}O_6$) known as glycolysis—in starches or sugars down into alcohol and carbon dioxide molecules. Alcoholic fermentation produces wine and beer.

3. Acetic acid fermentation. Starches and sugars from grains and fruit ferment into sour tasting vinegar and condiments. Examples include apple cider vinegar, wine vinegar, and kombucha.




Glycolysis
Fermentation
GLUCOSE
Pyruvic acid
Anaerobic bacteria
Yeast
Lactic acid fermentation
Alcohol fermentation
Aspergillus
Lactobacillus
Saccharomyces
Lactic acid i.e. Soy Sauce
Lactic acid i.e. Cheese & Yoghurt
Ethanol + CO2 i.e. Beer
Ethanol i.e. Wine
CO2 i.e. Bread

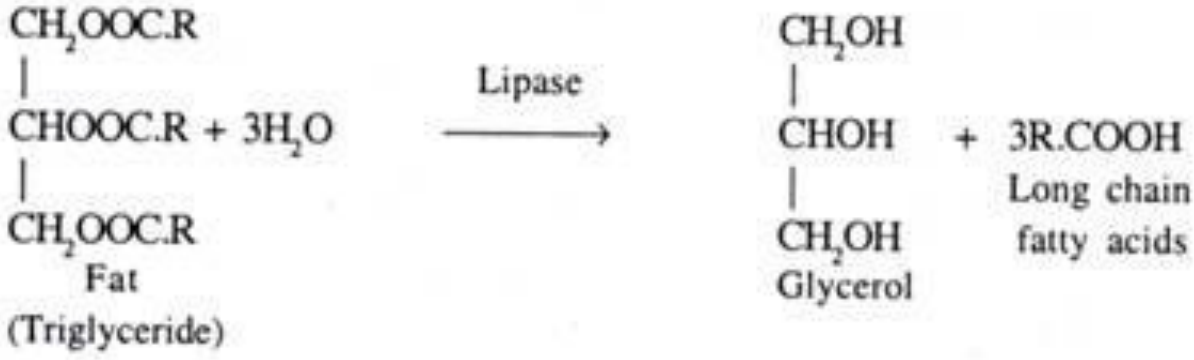

Pyruvate
NADH
NAD+
CO2
Acetaldehyde
Lactate
Acetyl CoA
Ethanol
Further oxidation
(Citric acid cycle, electron transport chain)

Lipid metabolism

Lipids are diverse group of organic compounds including fats, oils, hormones, and certain components of membranes that are grouped together because they do not interact appreciably with water. One type of lipid, the triglycerides, is sequestered as fat in adipose cells, which serve as the energy-storage depot for organisms and also provide thermal insulation. Some lipids such as steroid hormones serve as chemical messengers between cells, tissues, and organs, and others communicate signals between biochemical systems within a single cell. The membranes of cells and organelles (structures within cells) are microscopically thin structures formed from two layers of phospholipid molecules. Membranes function to separate individual cells from their environments and to compartmentalize the cell interior into structures that carry out special functions. So important is this compartmentalizing function that membranes, and the lipids that form them, must have been essential to the origin of life itself. Lipids are hydrophobic compounds. Although biological lipids are not large macromolecular polymers (e.g., proteins, nucleic acids, and polysaccharides), many are formed by the chemical linking of several small constituent molecules. Many of these molecular building blocks are similar, or homologous, in structure. The homologies allow lipids to be classified into a few major groups: fatty acids, fatty acid derivatives, cholesterol and its derivatives, and lipoproteins.

Biological fatty acids, members of the class of compounds known as carboxylic acids, are composed of a hydrocarbon chain with one terminal carboxyl group (COOH). The fragment of a carboxylic acid not including the hydroxyl (OH) group is called an acyl group. Under physiological conditions in water, this acidic group usually has lost a hydrogen ion (H^+) to form a negatively charged carboxylate group (COO^-). In addition to straight-chain hydrocarbons, fatty acids may also contain pairs of carbons linked by one or more double bonds, methyl branches, or a three-carbon cyclopropane ring near the center of the carbon chain.

Fats are degraded by lipase enzyme to produce glycerol and fatty acids according to the following equation:

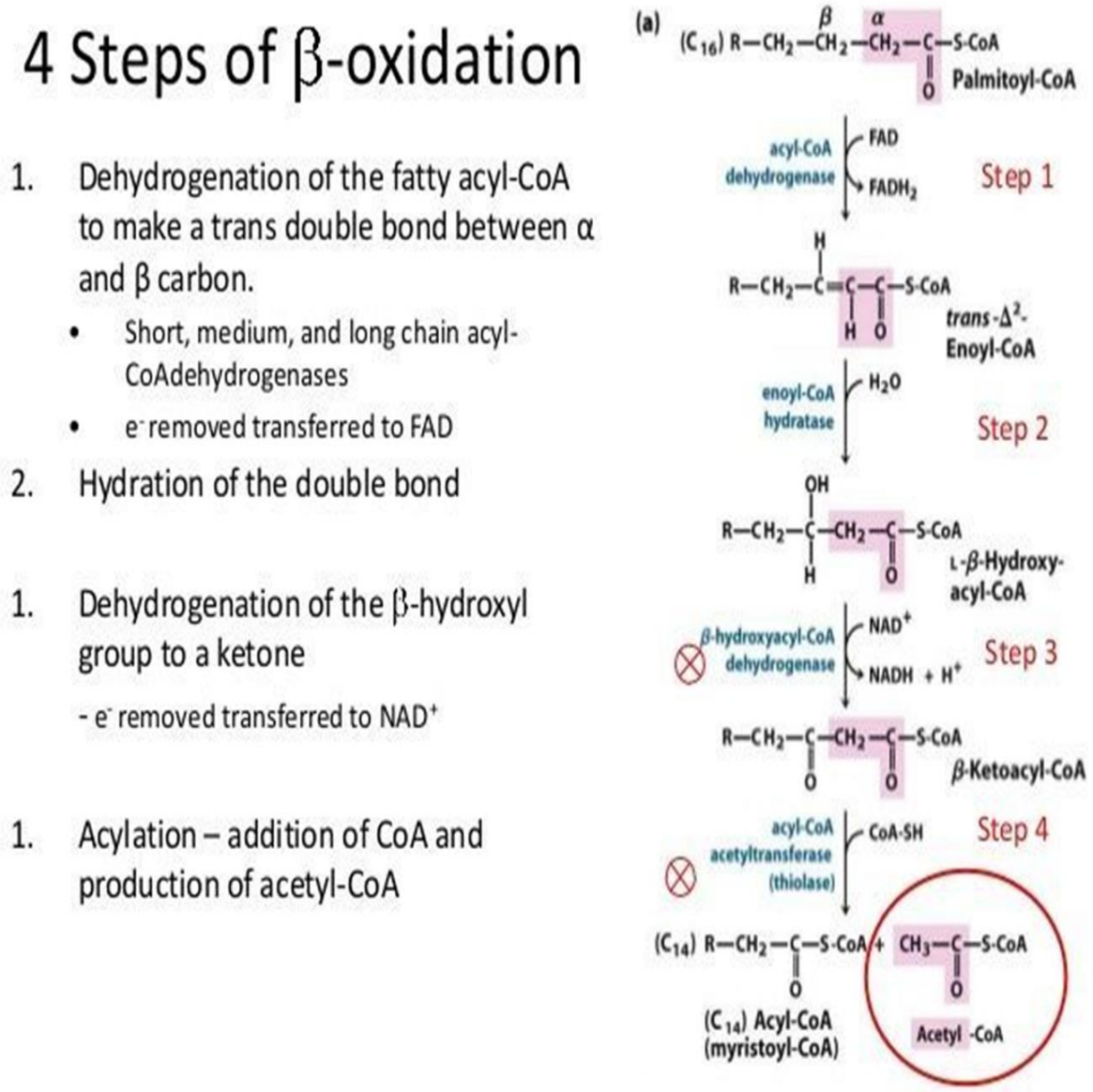


Beta oxidation

Lipids are abundant in host tissues, and fungal pathogens in the phylum basidiomycota possess both peroxisomal and mitochondrial β-oxidation pathways to utilize this potential carbon source. In addition, lipids are important signaling molecules in both fungi and mammals. They are degraded in the catabolic process called beta oxidation. During beta oxidation, the third (or beta) carbon of the saturated fatty acid chain of the fatty acyl CoA is oxidized to a ketone. β-Oxidation of fatty acids is important for the utilization of storage lipids or exogenous fatty acids to generate acetyl coenzyme A (acetyl-CoA) for central carbon metabolism. Most organisms have multiple enzymes for each of the four steps in β-oxidation to accommodate fatty acids of different chain length or saturation state. In mammals, β-oxidation occurs in both peroxisomes and mitochondria. The peroxisome is thought to be responsible for the oxidation of long-chain fatty acids, and the mitochondrion oxidizes short-chain fatty acids and also performs the final oxidation step. Fungal β-oxidation is not well characterized, and it was previously thought that fungi might have peroxisomal β-oxidation only because *Saccharomyces cerevisiae* lacks the enzymes for mitochondrial β-oxidation. However, recent in silico surveys of the pathways encoded in more than 50 fungal genomes revealed that most fungi possess both mitochondrial and peroxisomal pathways. Mitochondrial β-oxidation has also

been convincingly demonstrated in the saprophytic ascomycete *Aspergillus nidulans*.

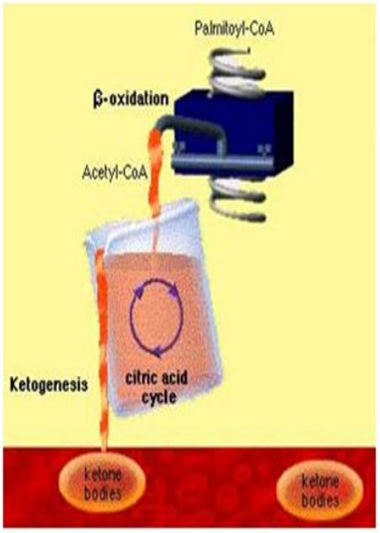
Beta oxidation is a spiral pathway. Each round consists of four enzyme-catalyzed steps that yield one molecule of acetyl CoA and an acyl CoA shortened by two carbons, which becomes the starting substrate for the next round. Seven rounds of beta oxidation degrade a C_{16} fatty acid to eight molecules of acetyl CoA. Complete oxidation of one molecule of palmitic acid to carbon dioxide and water yields 129 molecules of ATP. One round of beta oxidation yields 17 ATP.

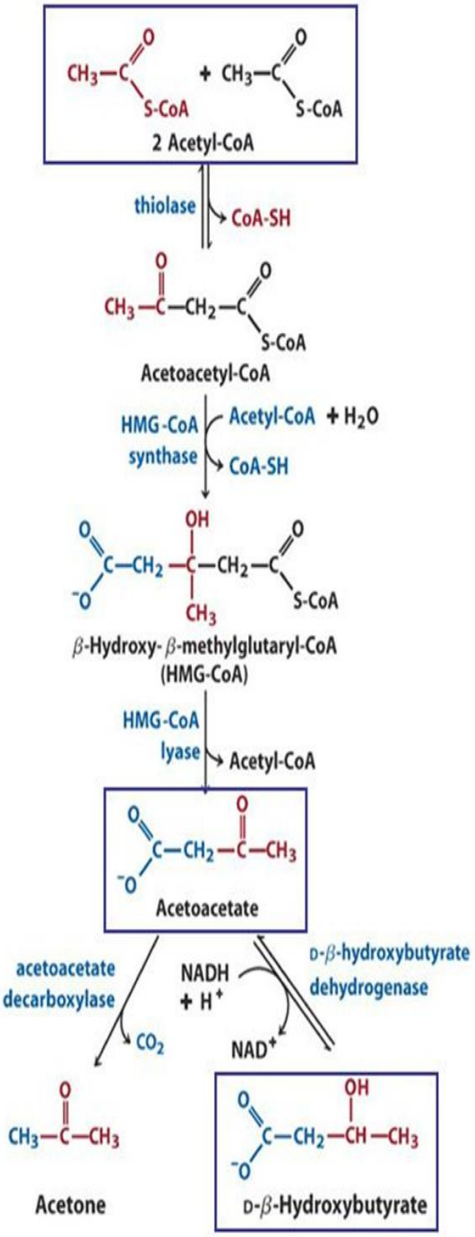


The reactions of ß-oxidation

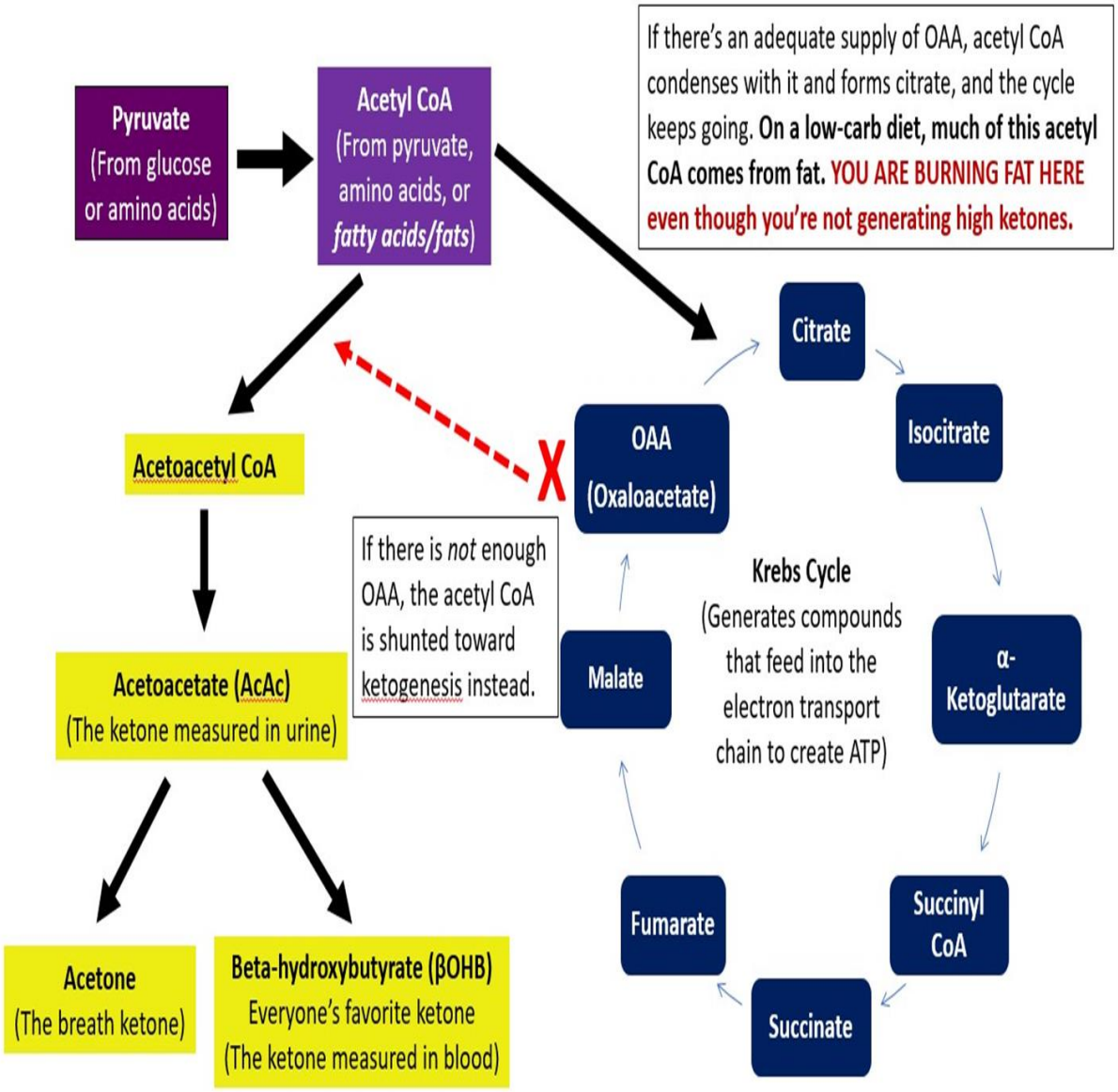
Ketogenesis

When fatty acid oxidation produces more acetyl-CoA than can be combined with OAA to form citrate, then the **"extra" acetyl-CoA** is converted to acetoacetyl-CoA and ketone bodies, including acetone. **Ketogenesis** (synthesis of ketone bodies) takes place primarily in the liver.

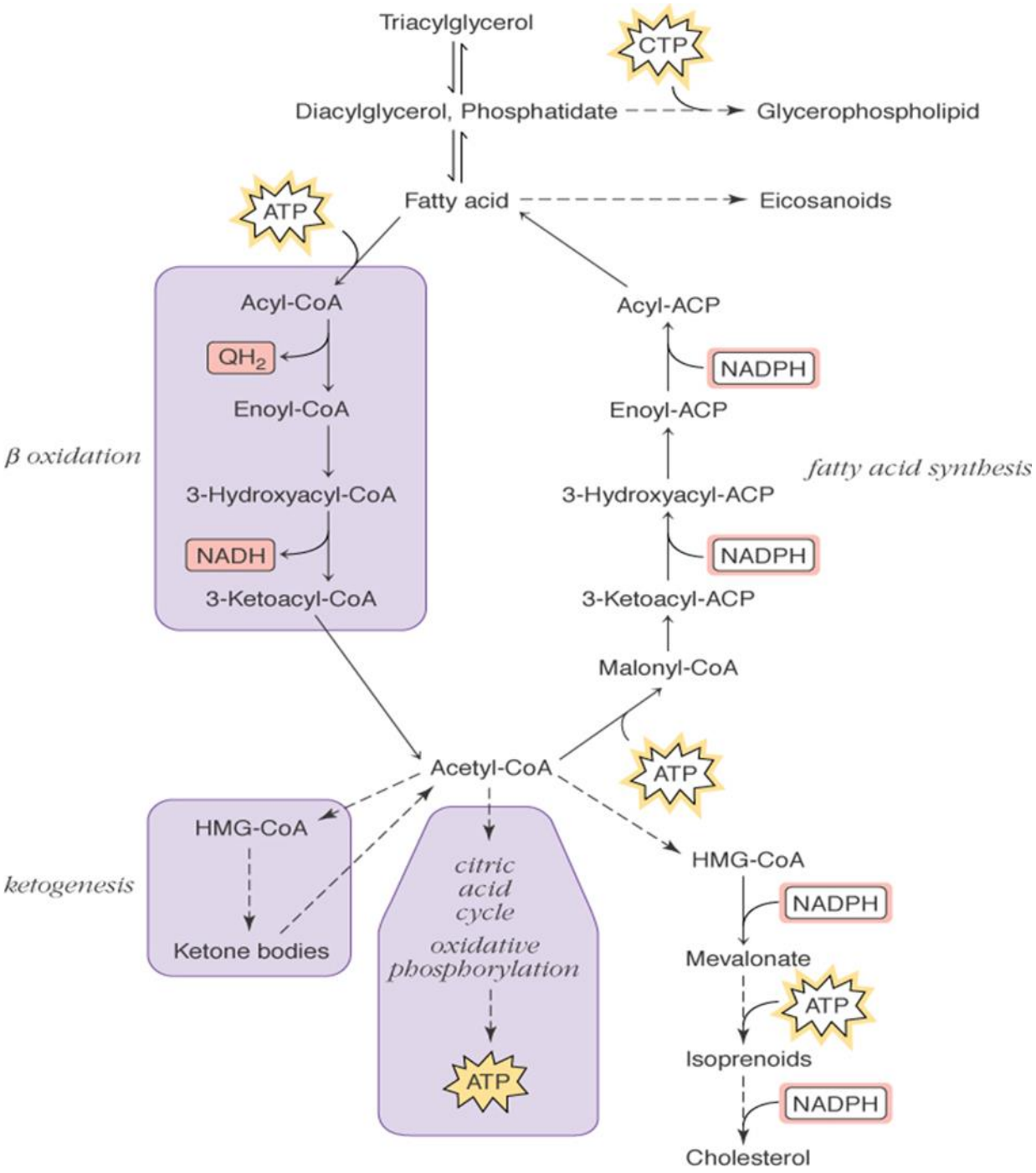




Ketogenesis and Krebs cycle



Summary of lipid metabolism



Nitrogen metabolism

Polymeric nitrogen containing compounds are proteins and nucleic acids that define the major attributes of organism such as function and structure. Operation and mechanism of metabolic pathways is provided by proteins. However genetic information is stored in nucleic acid polymers. Nitrogen is one of the most prevalent essential macro-elements which regulates fungal growth and metabolism. Anabolic processes includes: Nitrogen fixation (as in bacteria, e.g. *Rhizobium*), Amino acids synthesis, Protein synthesis. However, Catabolic processes includes: Proteolysis and amino acids destruction, Nitrification, denitrification.

Nitrification is the biological oxidation of ammonia or ammonium to nitrite followed by the oxidation of the nitrite to nitrate.

$NO_3+O_2+2e- \rightarrow NH_2OH + H_2O$

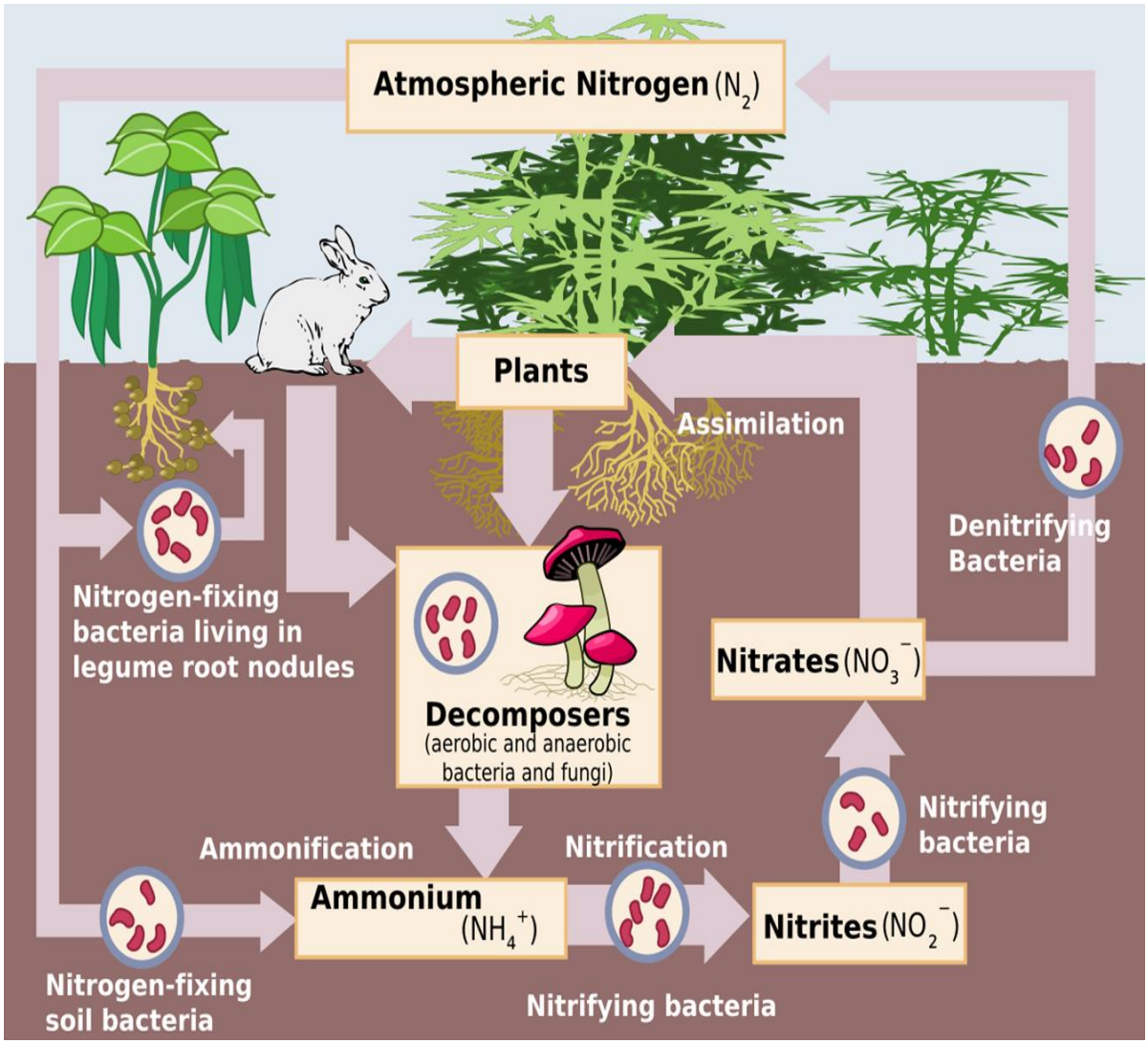
$NH_2OH +H_2O \rightarrow NO_2 +5\ H+ +4e-$

$NO_2 +O_2 \rightarrow NO_3$

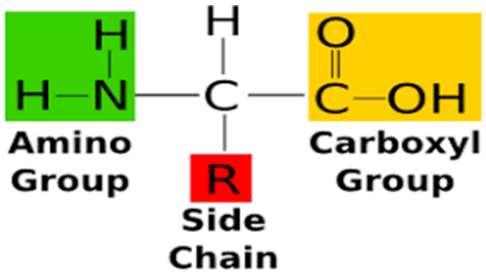
Denitrification is the process that coverts nitrate to nitrogen gas.

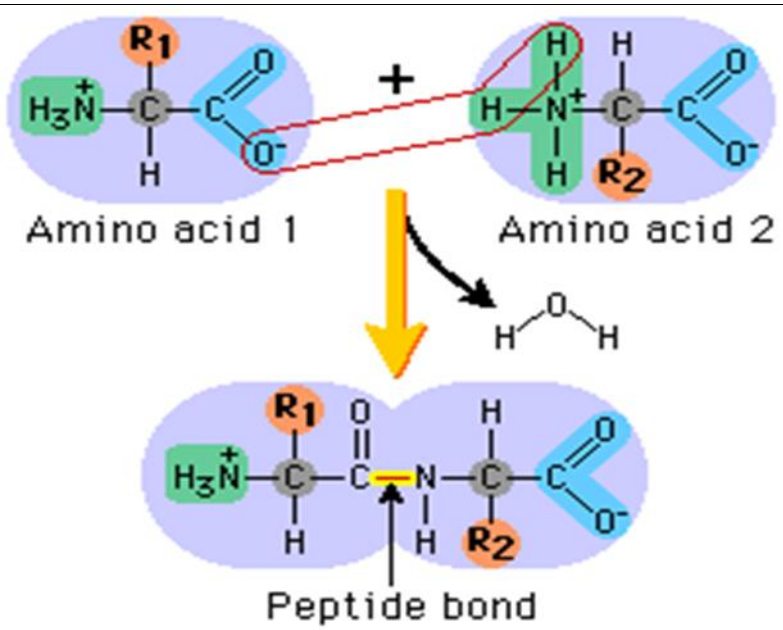
$NO_3 \rightarrow NO_2 \rightarrow NO + N_2O \rightarrow N_2$

Nitrogen cycle



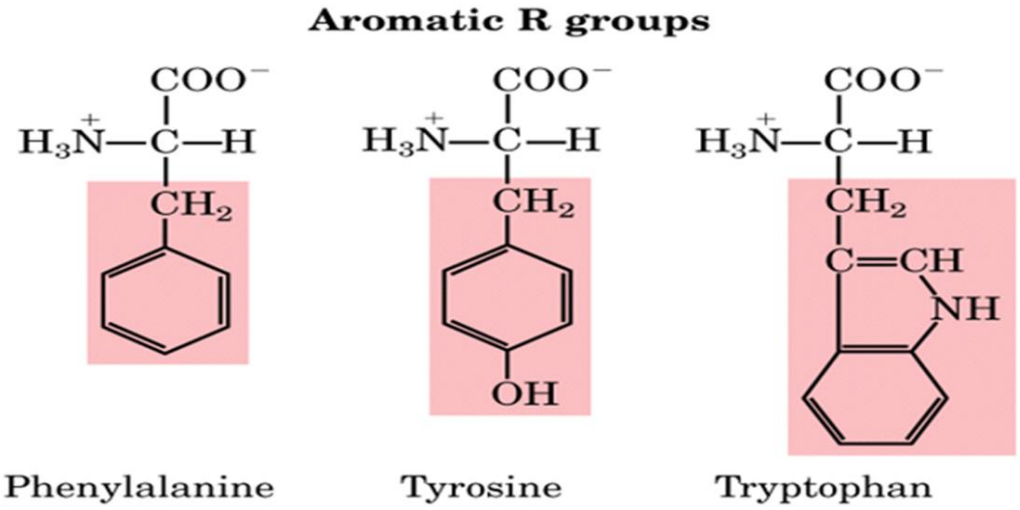
Amino acids

Amino acid structure	

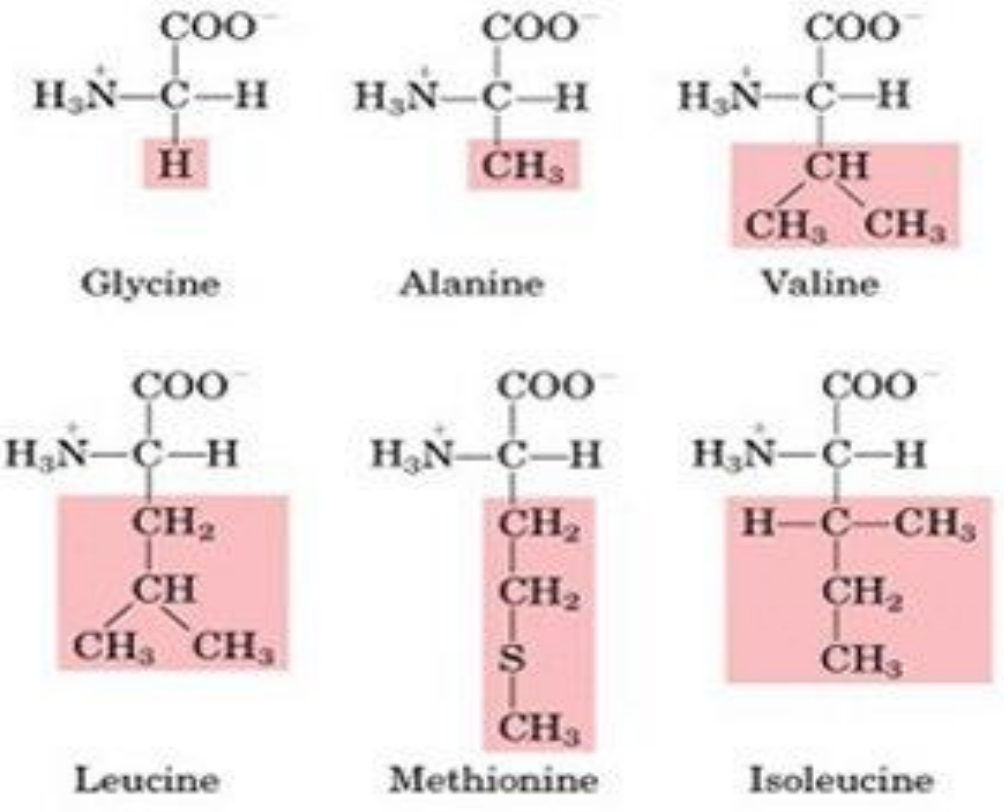
Formation of peptide bond	

Types of amino acids

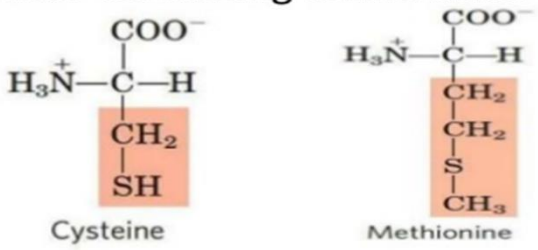
Aromatic amino acids



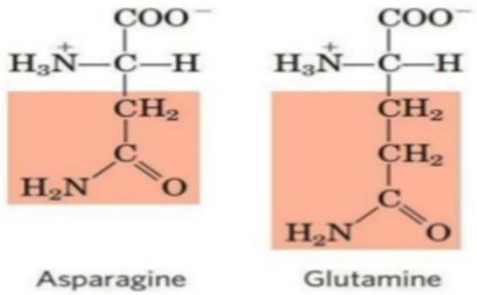
Aliphatic amino acid



❑ Sulfur-containing amino acids



❑ Amide group-containing amino acids



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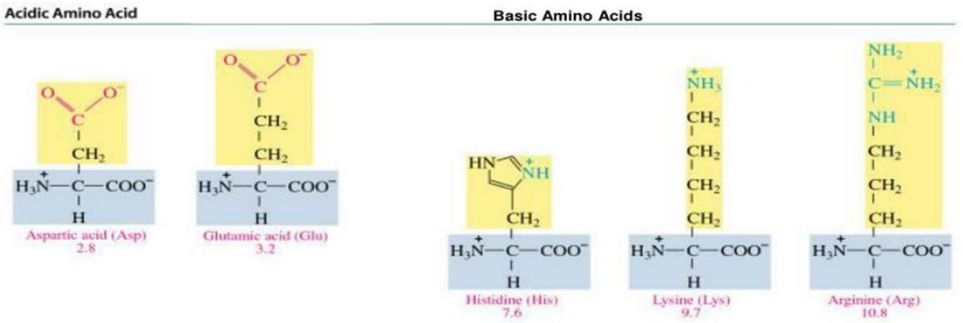
Acidic and Basic Amino Acids

An amino acid is

- Acidic with a carboxyl R group (COO^-).
- Basic with an amino R group (NH_3^+).



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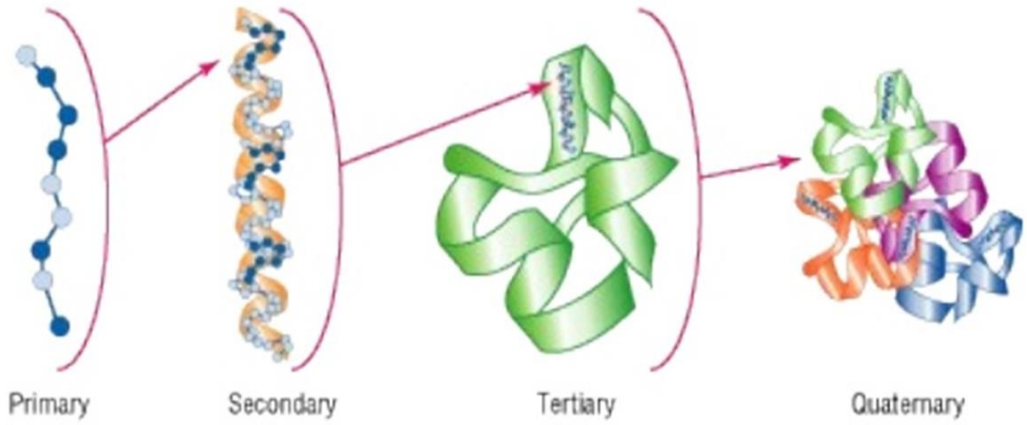
Protein structure

- Proteins, amino acid chains, can be any length and any combination.
- They have four levels of structure.



Antibiotics

Antibiotics are compounds of natural, semi-synthetic, or synthetic origin which inhibit growth of microorganisms without significant toxicity to the human or animal host. The key concept of antibiotic therapy is selectivity. The independent evolutionary history of bacterial (prokaryotic) and host (eukaryotic) cells led to a significant difference in cell organization, biochemical pathways and structures of proteins and RNA. These differences form the basis for drug selectivity.

Cell wall as antibiotic target

Most of the bacteria have a rigid cell wall which protects the cell from changes in osmotic pressure. Presence of the cell wall is critical for the survival of bacterial cell. The structure and composition of bacterial cell wall is dramatically different from the cell envelope of the eukaryotic cell. Therefore, enzymes of cell wall biosynthesis are unique to bacteria and presents an excellent target for antibiotics. According to the structure of their cell wall and staining procedure developed by Christian Gram in 1884, Bacteria are divided into Gram-positive and Gram-negative.

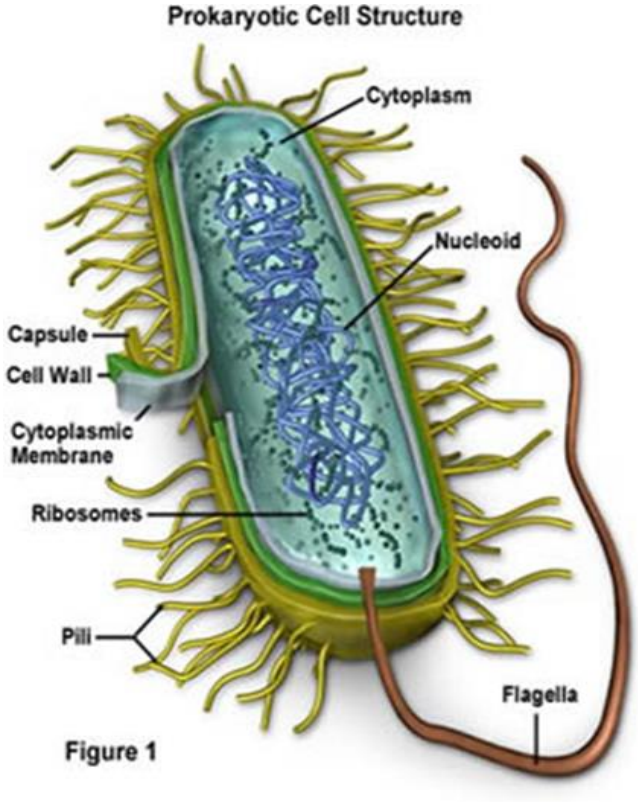
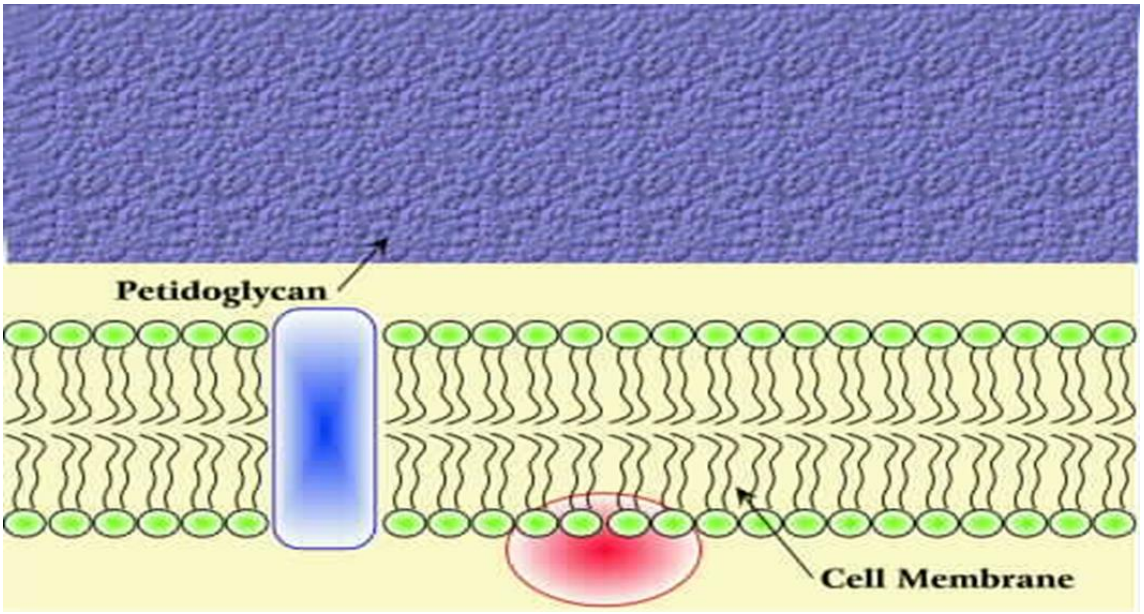


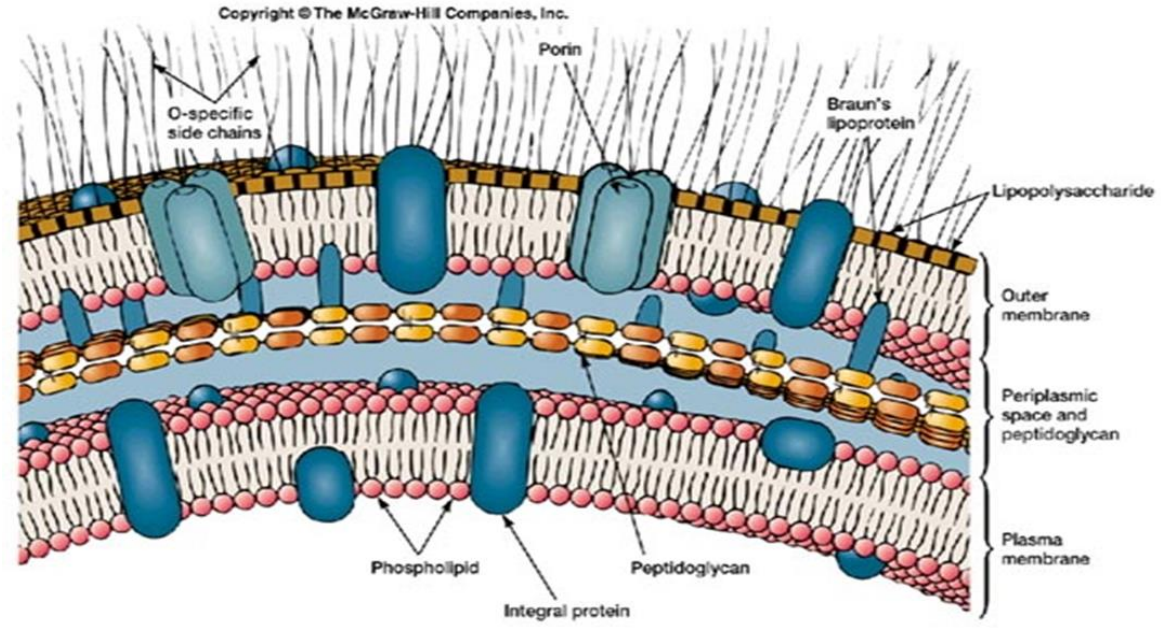
Figure 1

Cell wall of gram positive bacteria

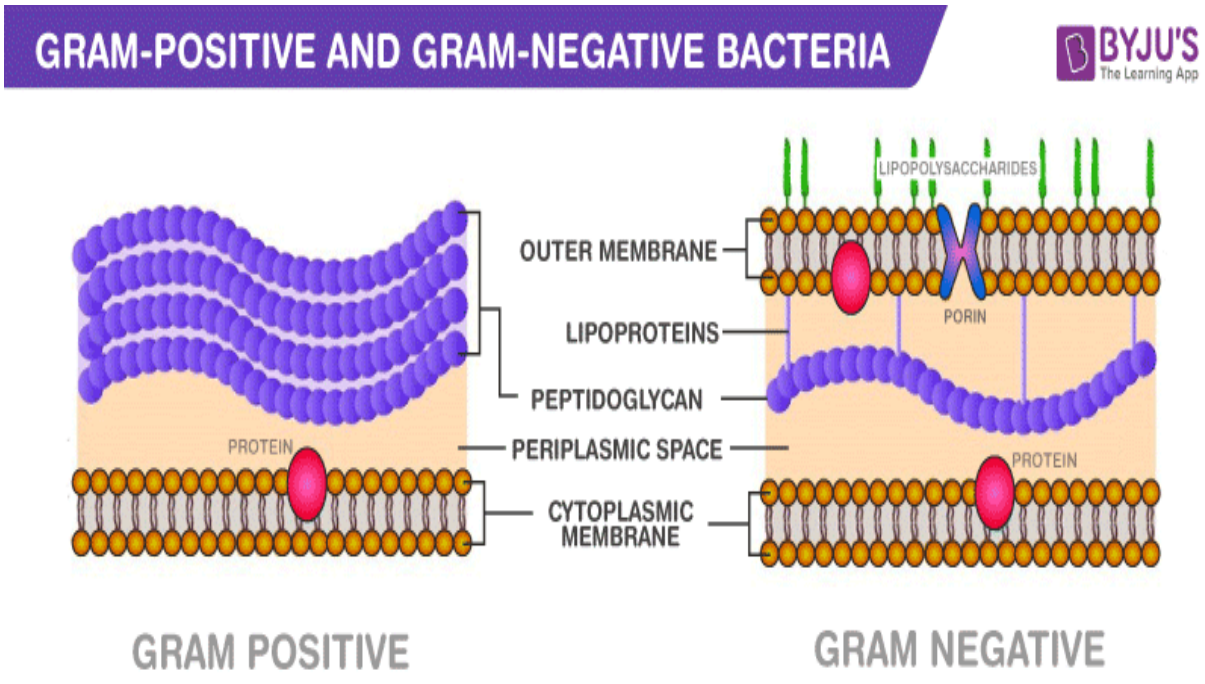


Outside of the cytoplasmic membrane of Gram-positive bacteria lies a thick layer of peptidoglycan which determines the rigidity of the cell wall. In Gram-positive bacteria, peptidoglycan accounts for 50% of the cell weight and up to 90% of the weight of the cell wall. Peptidoglycan layer is 20-80 nm thick. Peptidoglycan compose of polymer of N-acetyl glucosamine and N-acetyl muramic acid.

Cell wall of gram negative bacteria

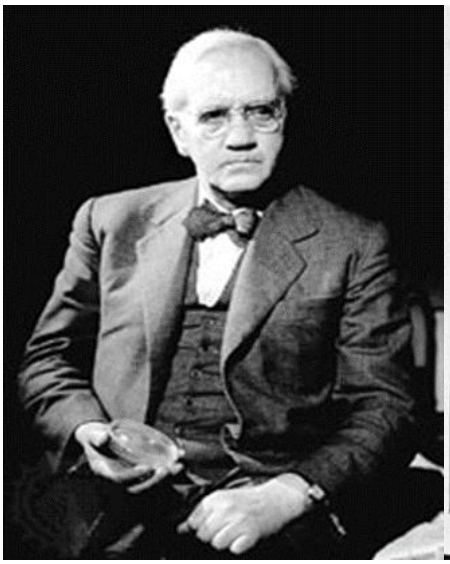


The cell wall of Gram-negative bacteria consists of the cytoplasmic membrane, a thin layer of peptidoglycan, and an outer membrane. The area between the cytoplasmic membrane and peptidoglycan layer is called the periplasmic space.



Discovery of penicillin

The discovery of penicillin is usually attributed to Scottish Scientist Sir Alexander Fleming in 1928, though others had earlier noted the antibacterial effects of *Penicillium*. The development of penicillin for use as a medicine is attributed to the Australian Nobel Laureate Howard Walter Florey. In March 2000, doctors of the San Juan de Dios Hospital in San Jose (Costa Rica) published manuscripts belonging to the Costa Rican scientist and medical doctor Clodomiro (Clorito) Picado Twight (1887-1944). The manuscripts explained Picado's experiences between 1915 and 1927 about the inhibitory actions of the fungi of genus *Penicillium*. Apparently Clorito Picado had reported his discovery to the Paris Academy of Sciences in Paris, yet did not patent it, even though his investigation had started years before Fleming's. Fleming, at his laboratory in St. Mary's Hospital (now one of Imperial College's teaching hospitals) in London, noticed a halo of inhibition of bacterial growth around a contaminant blue-green mold *Staphylococcus* plate culture. Fleming concluded that the mold was releasing a substance that was inhibiting bacterial growth and lysing the bacteria. He grew a pure culture of the mold and discovered that it was a *Penicillium* mold, now known to be *Penicillium notatum*. Fleming coined the term "penicillin" to describe the filtrate of a broth culture of the *Penicillium* mold. Even in these early stages, penicillin was found to be most effective against Gram-positive bacteria, and ineffective against Gram-negative organisms and fungi. He expressed initial optimism that penicillin would be a useful disinfectant, being highly potent with minimal toxicity compared to antiseptics of the day, but particularly noted its laboratory value in the isolation of "*Bacillus influenzae*" (now *Haemophilus influenzae*). After further experiments, Fleming was convinced that penicillin could not last long enough in the human body to kill pathogenic bacteria and stopped studying penicillin after 1931, but restarted some clinical trials in 1934 and continued to try to get someone to purify it until 1940.



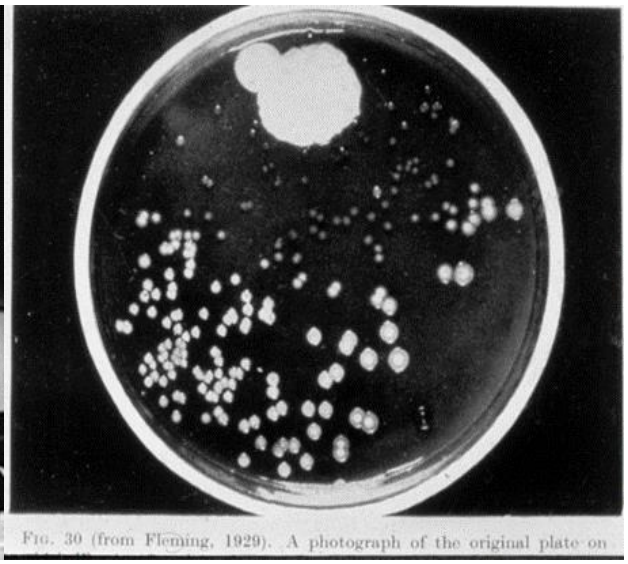


Fig. 30 (from Fleming, 1929). A photograph of the original plate on

In 1939, Australian scientist Howard Walter Florey and a team of researchers (Ernst Boris Chain, A. D. Gardner, Norman Heatley, M. Jennings, J. Orr-Ewing and G. Sanders) at the Sir William Dunn School of Pathology, University of Oxford made significant progress in showing the in vivo bactericidal action of penicillin. Their attempts to treat humans failed due to insufficient volumes of penicillin (the first patient treated was Reserve Constable Albert Alexander), but they proved its harmlessness and effect on mice.

A moldy cantaloupe in a Peoria market in 1941 was found to contain the best and highest quality penicillin after a world-wide search. Some of the pioneering trials of penicillin took place at the Radcliffe Infirmary in Oxford. On March 3, 1942 John Bumstead and Orvan Hess became the first in the world to successfully treat a patient using penicillin. Penicillin was being mass-produced in 1944.

During World War II, penicillin made a major difference in the number of deaths and amputations caused by infected wounds amongst Allied forces; saving an estimated 12-15% of lives. Availability was severely limited, however, by the difficulty of manufacturing large quantities of penicillin and by the rapid renal clearance of the drug necessitating frequent dosing. Penicillins are actively

secreted and about 80% of a penicillin dose is cleared within three to four hours of administration.

This was not a satisfactory solution, however, so researchers looked for a way to slow penicillin secretion. They hoped to find a molecule that could compete with penicillin for the organic acid transporter responsible for secretion such that the transporter would preferentially secrete the competitive inhibitor. The uricosuric agent probenecid proved to be suitable. When probenecid and penicillin are concomitantly administered, probenecid competitively inhibits the secretion of penicillin, increasing its concentration and prolonging its activity. The advent of mass-production techniques and semi-synthetic penicillins solved supply issues, and this use of probenecid declined. Probenecid is still clinically useful, however, for certain infections requiring particularly high concentrations of penicillins.

The chemical structure of penicillin was determined by Dorothy Crowfoot Hodgkin in the early 1940s. A team of Oxford research scientists led by Australian Howard Walter Florey and including Ernst Boris Chain and Norman Heatley discovered a method of mass producing the drug. Chemist John Sheehan at MIT completed the first total synthesis of penicillin and some of its analogs in the early 1950s, but his methods were not efficient for mass production. Florey and Chain shared the 1945 Nobel prize in medicine with Fleming for this work. Penicillin has since become the most widely used antibiotic to date and is still used for many Gram-positive bacterial infections.

Structure and types of Penicillin

Penicillins are a group of β-lactam antibiotics consisting of natural penicillins and semisynthetic penicillins. The basic structure of all penicillins, natural and semisynthetic, is 6-aminopenicillanic acid composed of a four membered heterocyclic β-lactam ring fused with a five membered (benzylpenicillin), penicillin V (Phenoxymethyl penicillin), thiazolidine ring.

This basic structure combines with N-acyl group which is variable and shows structural differences in different type of penicillins. The N-acyl group is the side chain attached to the amino group of 6-aminopenicillanic acid. However, there are three natural penicillins that are produced directly and can be obtained from the fermentation Iiquours of *Pencillium*.

These are penicillin G and penicillin F (phentenyl penicillin). Natural penicillins are obtained as salts of sodium (Na) or potassium (K) or procaine. The structures of natural penicillins as Na-salts.

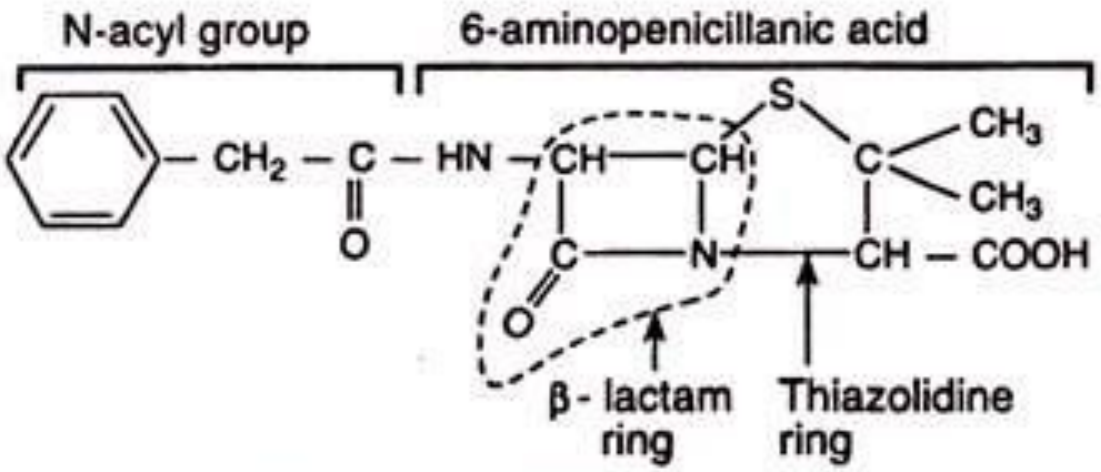


FIG. 45.6. Basic structure of penicillins.

Developments from penicillin

The narrow spectrum of activity of the penicillins, along with the poor activity of the orally-active phenoxymethylpenicillin, led to the search for derivatives of penicillin which could treat a wider range of infections.

The first major development was ampicillin, which offered a broader spectrum of activity than either of the original penicillins. Further development yielded beta-lactamase-resistant penicillins including flucloxacillin, dicloxacillin and methicillin. These were significant for their activity against beta-lactamase-

producing bacteria species, but are ineffective against the methicillin-resistant *Staphylococcus aureus* strains that subsequently emerged.

The line of true penicillins were the antipseudomonal penicillins, such as ticarcillin and piperacillin, useful for their activity against Gram-negative bacteria. However, the usefulness of the beta-lactam ring was such that related antibiotics, including the mecillinams, the carbapenems and, most importantly, the cephalosporins, have this at the center of their structures.

Mechanism of action of beta-lactam antibiotic

β-lactam antibiotics work by inhibiting the formation of peptidoglycan cross-links in the bacterial cell wall. The β-lactam moiety (functional group) of penicillin binds to the enzyme (DD-transpeptidase) that links the peptidoglycan molecules in bacteria, and this weakens the cell wall of the bacterium (in other words, the antibiotic causes cytolysis or death). In addition, the build-up of peptidoglycan precursors triggers the activation of bacterial cell wall hydrolases and auto lysins which further digest the bacteria's existing peptidoglycan.

When the bacteria lose their cell walls they are then called spheroplasts. Penicillin shows a synergistic effect with aminoglycosides since the inhibition of peptidoglycan synthesis allows aminoglycosides to penetrate the bacterial cell wall more easily, allowing its disruption of bacterial protein synthesis within the cell. This results in a lowered MBC for susceptible organisms.

Benzylpenicillin, commonly known as penicillin G, is the gold standard penicillin. Penicillin G is typically given by a parenteral route of administration (not orally) because it is unstable in the hydrochloric acid of the stomach. Because the drug is given parenterally, higher tissue concentrations of penicillin G can be achieved than is possible with phenoxymethylpenicillin. These higher concentrations translate to increased antibacterial activity.

Phenoxymethylpenicillin, commonly known as penicillin V, is the orally-active form of penicillin. It is less active than benzylpenicillin, however, and is only appropriate in conditions where high tissue concentrations are not required.

Semi-synthetic penicillins

Structural modifications were made to the side chain of the penicillin nucleus in an effort to improve oral bioavailability, improve stability to beta-lactamase activity, and increase the spectrum of action.

Narrow spectrum penicillinase-resistant penicillins

This group was developed to be effective against beta-lactamases produced by *Staphylococcus aureus*, and are occasionally known as anti-staphylococcal penicillin. Penicillin is rampantly used for curing infections and to prevent growth of harmful mold.

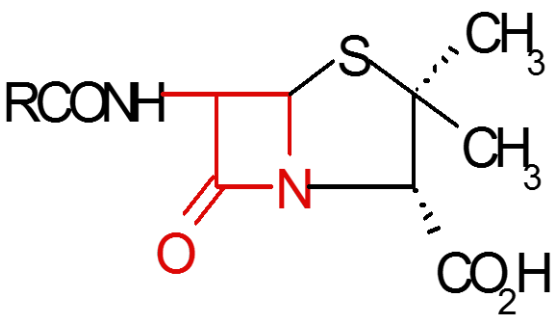
Narrow spectrum β-lactamase-resistant penicillins

This molecule has a spectrum directed towards Gram negative bacteria without activity on *Pseudomonas aeruginosa* or *Acinetobacter* spp. with remarkable resistance to any type of β-lactamase.

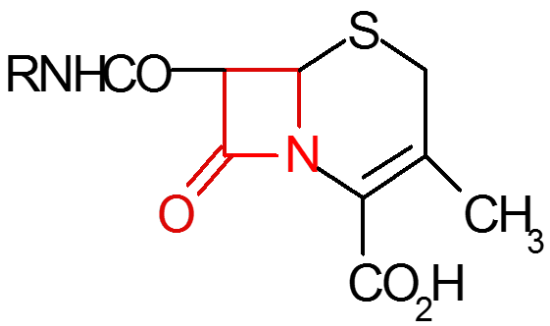
Commercial production of penicillin

Development of methods for growing *Penicillium notatum* and purifying Penicillin and chain made it into a drug. The deep fermentation method, the use of corn steep liquor and the discovery of *P. chrysogenum* made the commercial production of penicillin possible.

β-lactam antibiotics



Penicillins

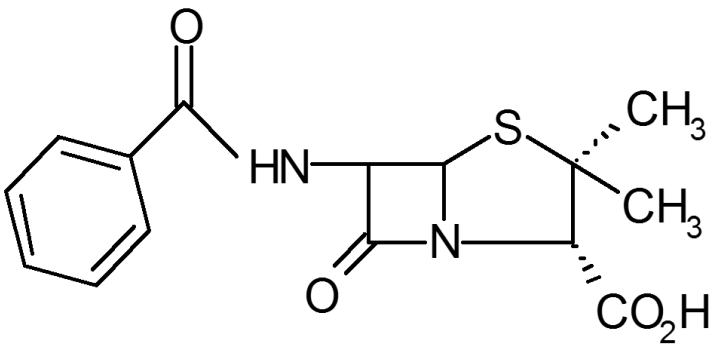


Cephalosporins

The most important class of antibiotics affecting cell wall biosynthesis are β-lactams. β-lactam group (a four-atom cyclic amide) is the pharmacophore of all β-lactam antibiotics. β-lactam rings were unknown before the discovery of penicillin and it took big effort to determine the structure of the drug. The most important classes of β-lactam antibiotics are penicillins and cephalosporins.

Penicillin G

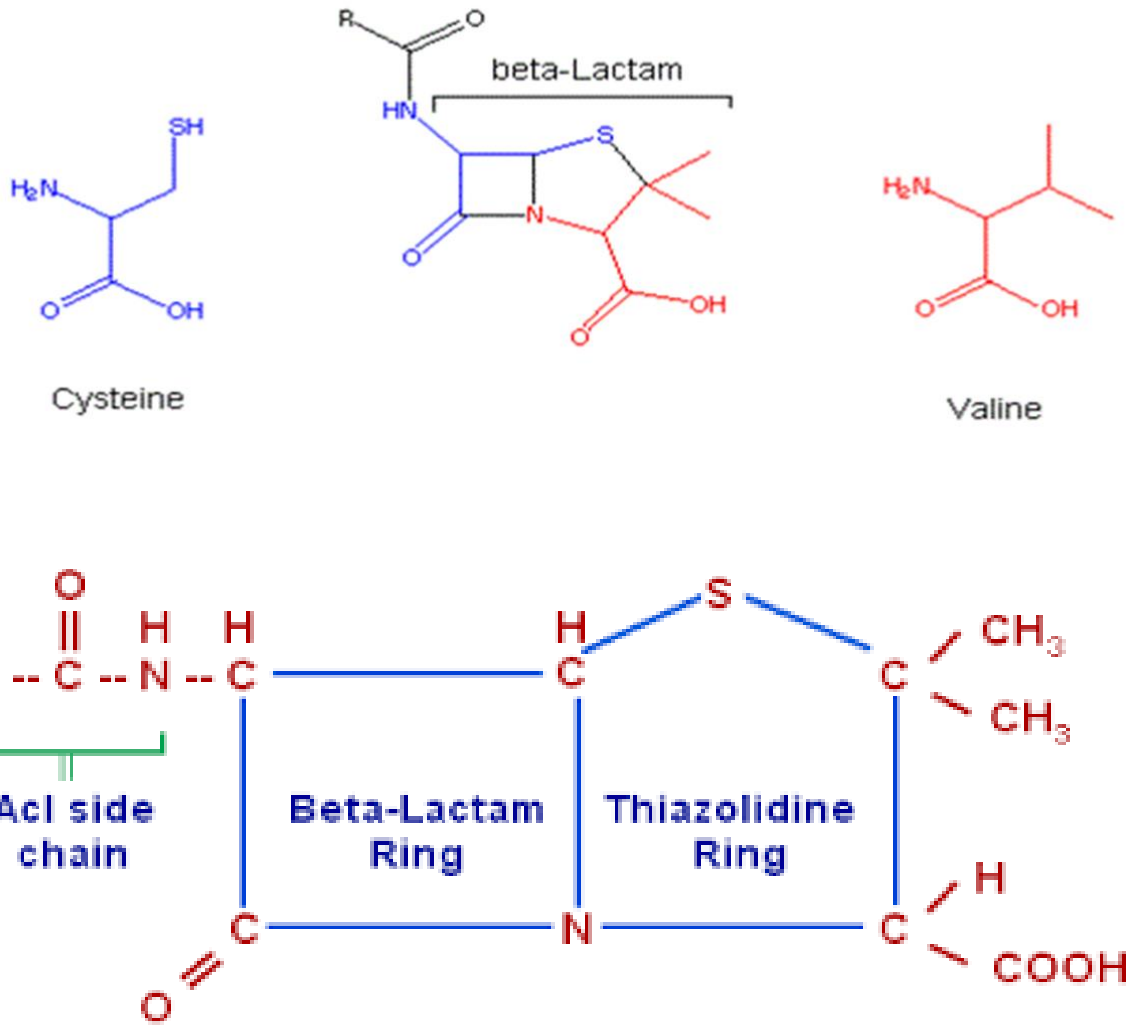
In penicillins, the β-lactam ring is fused to thiazolidine ring. Originally, penicillin was produced in the form of Penicillin G (benzylpenicillin) by fermenting *Penicillium* mold in the presence of phenyl acetic acid as a precursor. It has good activity against Gram-positive bacteria.



Benzylpenicillin (penicillin G)

Biosynthesis of Penicillins

b-lactam antibiotics are produced by fungi, some ascomycetes, and several actinomycete bacteria. Pencillins are synthesized from two amino acids (valine and cysteine).



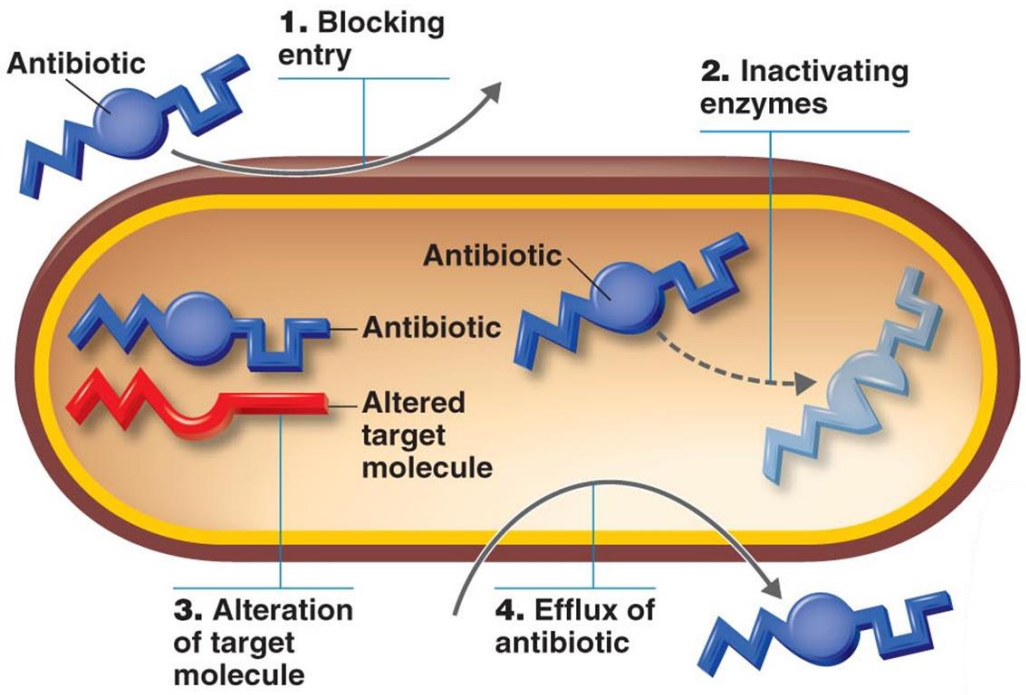
6-Aminopenicillanic acid (6-APA)

Presently, many penicillins are produced semisynthetically starting from 6-aminopenicillanic acid (6-APA) as a precursor. 6-APA can be generated from penicillin G by cleaving off the benzyl moiety of penicillin G. Various new side chains can be then attached to the penicillin molecule through the amino group of 6-APA.

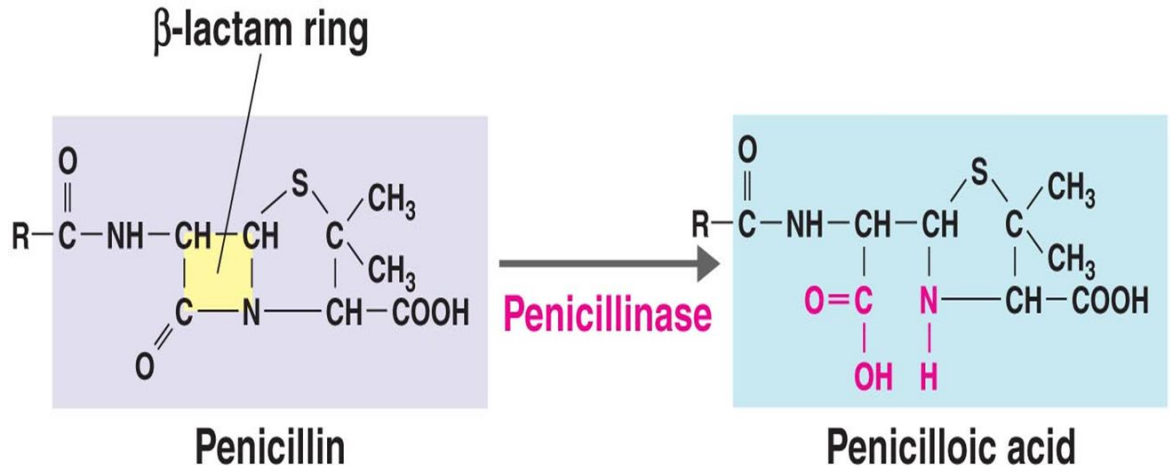
Mechanisms of antibiotic resistance

1- Enzymatic destruction of drug
2- Prevention of penetration of drug
3- Alteration of drug's target site
4- Rapid ejection of the drug

Resistance genes are often on plasmids or transposons that can be transferred between bacteria.

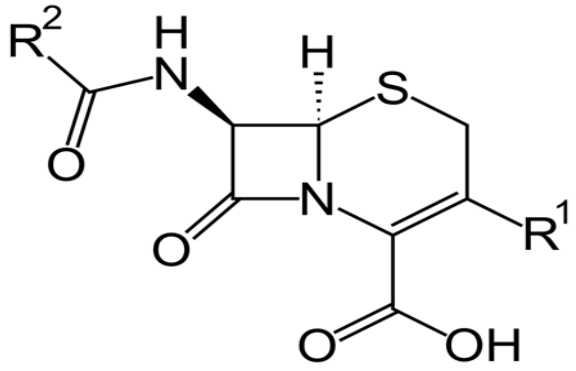


Penicillinase (β-lactamase): bacterial enzyme that destroys natural penicillins



Cephalosporins

Cephalosporins have been first obtained from a fungus *Cephalosporium acremonium*. Similar to penicillins, many cephalosporins are produced semi-synthetically either starting from 7-aminocephalosporanic acid (7-ACA) or by converting relevant penicillins into cephalosporins.



Antibiotic Susceptibility Testing (Minimum inhibitory concentration, MIC)

Susceptibility is a term used when microbe such as bacteria and fungi are unable to grow in the presence of one or more antimicrobial drugs. Susceptibility testing

is performed on bacteria or fungi causing an individual's infection after they have been recovered in a culture of the specimen. Testing is used to determine the potential effectiveness of specific antibiotics on the bacteria and/or to determine if the bacteria have developed resistance to certain antibiotics. The results of this test can be used to help select the drug(s) that will likely be most effective in treating an infection.

Bacteria and fungi have the potential to develop resistance to antibiotics and antifungal drugs at any time. This means that antibiotics once used to kill or inhibit their growth may no longer be effective.

During the culture process, pathogens are isolated (separated out from any other microbes present). Each pathogen, if present, is identified using biochemical, enzymatic, or molecular tests. Once the pathogens have been identified, it is possible to determine whether susceptibility testing is required. Susceptibility testing is not performed on every pathogen; there are some that respond to established standard treatments. For example, strep throat, an infection caused by *Streptococcus pyogenes* (also known as group A streptococcus), can be treated with ampicillin and does not require a test to predict susceptibility to this class of antibiotics.

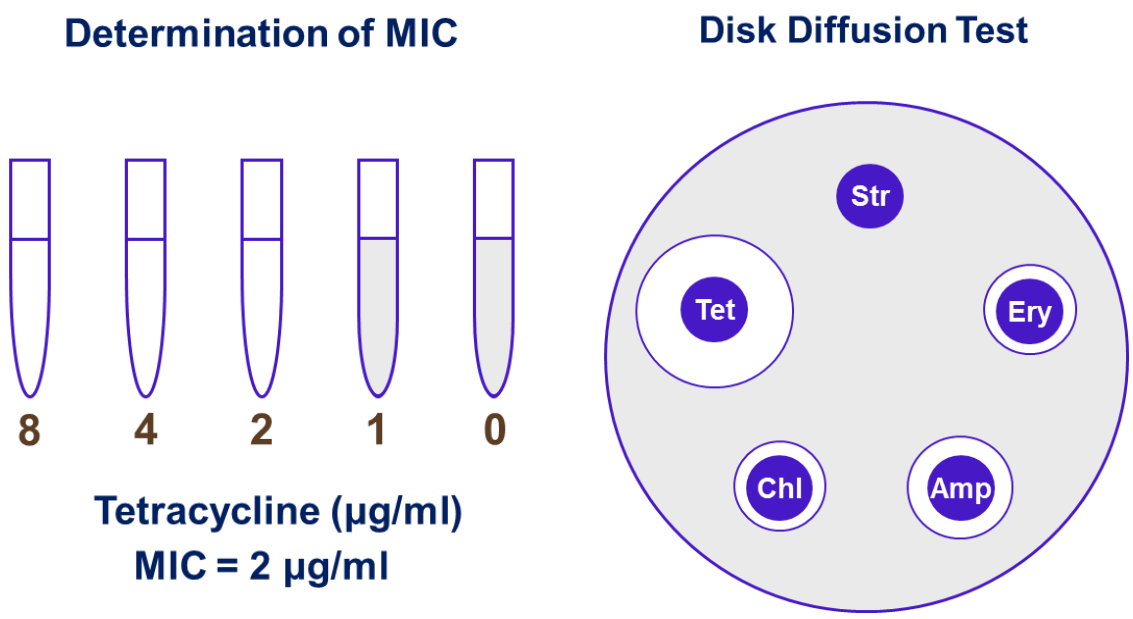
Susceptibility testing is performed on each type of bacteria or fungi that may be relevant to the individual's treatment and whose susceptibility to treatment may not be known. Each pathogen is tested individually to determine the ability of antimicrobials to inhibit its growth. This is can be measured directly by bringing the pathogen and the antibiotic together in a growing environment, such as nutrient media in a test tube or agar plate, to observe the effect of the antibiotic on the growth of the bacteria. Resistance can also be determined by detection of a gene that is known to cause resistance to specific antibiotics.

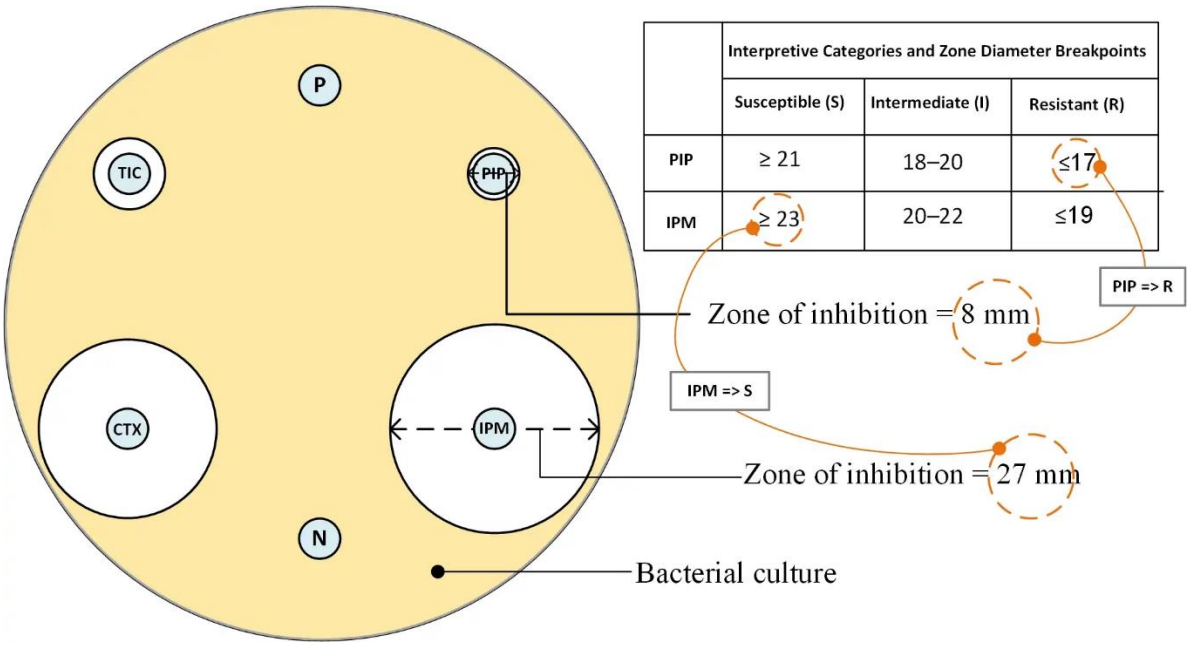
Susceptibility testing is used to determine which antimicrobials will inhibit the growth of the bacteria or fungi causing a specific infection. The results from this

test will help a health care practitioner determine which drugs are likely to be most effective in treating a person's infection.

Some types of infections may require testing because the bacteria or fungi isolated from an infection site are known to have unpredictable susceptibility to the drugs usually used to treat them. Some examples include staphylococci ("staph") and *Pseudomonas aeruginosa*.

Sometimes there may be more than one type of pathogen isolated from an infected site, such as a wound infection. Susceptibility testing may be used to determine which antibiotic or antibiotic combinations will be most effective in treating all the different types of bacteria causing the infection.





	Interpretive Categories and Zone Diameter Breakpoints		
	Susceptible (S)	Intermediate (I)	Resistant (R)
PIP	≥ 21	18–20	≤17
IPM	≥ 23	20–22	≤19

The medium used for the majority of bacterial species is Mueller-Hinton agar (plus 5% blood for fastidious germs):

- It shows acceptable lot-to-lot reproducibility for susceptibility testing.
- It is low in inhibitors which affect sulfonamide, trimethoprim and tetracycline susceptibility test results.
- It supports satisfactory growth of most pathogens.
- A large amount of data and experience has been collected on sensitivity tests carried out with this medium.