Module 8 – Diversity of Microbial World

Lecture 1- Microbial Taxonomy and Phylogeny

Introduction

Living organisms are fascinating by its diversity whether it is plants, animals or microbes. A handful of soil is populated with more than the human population on earth. They play important essential roles in nature. So if we arrange these microbes in order or hierarchy by based on its similarity or differences in any characteristics, we can easily get to know and get easy access to all the microbes. So it is desirable to determine the classification. Greek Philosopher Aristotle who is the one classified the living things as plants and animals around 2000 years ago. So in this lecture, we will learn about taxonomy, how is it classified? What methods are available to classify them? And then brief description about microbial evolution and diversity and its phylogeny.

Taxonomy

Taxonomy [Greek.taxis, arrangement, and nomos, law, or nemein, to distribute] is defined as the science of biological classification. In simple term, taxonomy is orderly arranging organisms under study into groups of larger units. It consists of three interrelated parts namely

1. Classification is the arrangement of organisms into groups or taxa (s., taxon) based on mutual similarity or evolutionary relatedness.
2. Nomenclature is concerned with the assignment of names to taxonomic groups in agreement with published rules.
3. Identification is the practical side of taxonomy, the process of determining that a particular isolate belongs to a recognized taxon. (So in short Identify-Naming them and classify them)

Classification

It is bringing order to the diverse variety of organisms present in nature. So there are two general ways the classification can be constructed. First one is based on the morphological characters (phenetic classification) and second is based on evolutionary relationship (phylogenetic classification)

Phenetic classification- Grouping organisms together based on the mutual similarity of their phenotypic characteristics. It does not provide information about phylogenetic relations.
Phylogenetic classification - These are systems based on evolutionary relationships rather than external appearance (the term phylogeny [Greek phylon, tribe or race, and genesis, generation or origin] refers to the evolutionary development of a species). It is based on the direct comparison of genetic materials and/or gene product.

Nomenclature (Binomial system)

Biologists in the middle ages used to follow polynomial system, i.e naming organisms with many names (poly-many, nomo-name). For example name for the European honeybee, was **Apis pubescens, thorace subgriseo, abdomen fisco, pedibus posticis glbris utrinec margine ciliatis** (just for example no need to be memorized). Later Binomial systems were developed by Swedish biologist Carolus Linnaeus (1707–1778) based on the anatomical characteristics of plants and animals. Nomenclature in microbiology is developed based on the principles established for the plant and Animal kingdom by Linnaeus. The first word in the binomial is the genus name and is always capitalized. The second word is species name and never capitalized. For example honeybee, *Apis mellifera*

**Taxonomic ranks:**

In prokaryotic taxonomy the most commonly used levels or ranks (in ascending order) are species, genera, families, orders, classes, phyla, kingdom or domain. In order to remember the seven categories of the taxonomic hierarchy in their proper order, it may be useful to memorize a phrase such as “**k**indly **p**ay **c**ash or **f**urnish **g**ood **s**ecurity” (**k**ingdom–**p**hylum–**c**lass–**o**rder–**f**amily–**g**enus–**s**pecies). The basic taxonomic group in microbial taxonomy is the **species**.

A **species** is a collection of strains that have a similar G+C composition and **70% or greater similarity** as judged by DNA hybridization. Ideally a species also should be **phenotypically distinguishable** from other similar species. An example of hierarchy in taxonomy is given below.
<table>
<thead>
<tr>
<th>Rank</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Domain</td>
<td>Bacteria</td>
</tr>
<tr>
<td>Phylum</td>
<td>Proteobacteria</td>
</tr>
<tr>
<td>Class</td>
<td>γ-Proteobacteria</td>
</tr>
<tr>
<td>Order</td>
<td>Enterobacteriales</td>
</tr>
<tr>
<td>Family</td>
<td>Enterobactericeae</td>
</tr>
<tr>
<td>Genus</td>
<td>Shigella</td>
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<tr>
<td>Species</td>
<td>S.dysentriae</td>
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</tbody>
</table>

A **strain** is a population of organisms that is distinguishable from at least some other populations within a particular taxonomic category. It is considered to have descended from a single organism or pure culture isolate. Strains within a species *may differ slightly from one another* in many ways. **Biovars** are variant prokaryotic strains characterized by *biochemical or physiological differences*, **morphovars** differ *morphologically*, and **serovars** have distinctive *antigenic properties*. One strain of a species is designated as the **type strain**. It is usually one of the first strains studied and often is *more fully characterized* than other strains; however, it does not have to be the most representative member but this strain can be considered as reference strain and can be compared with other strains. Each species is assigned to a genus, the next rank in the taxonomic hierarchy. A **genus** is a well-defined group of one or more species that is clearly separate from other genera.

**Techniques for identifying or determining taxonomical characters**

In order to identify and classify microorganisms, we need to know about their characteristics. There are two ways to determine the taxonomical characters; *classical* and *molecular characters*

**Classical characteristics:-** This approach uses morphological, biochemical, physiological, ecological and genetic characteristics. It is mainly used in microbial taxonomy.
1. **Morphology:** Morphology is the one which can be easily studied and analyzed. Structural features (*cell shape, size, colony morphology, appendages, and etc.*) depend on the expression of many genes, are usually genetically stable.

2. **Physiology and metabolism:** Organisms are classified based on the requirements for growth characters like carbon and nitrogen sources, cell wall constituents, general nutritional type, energy sources, optimum growth temperature, Motility.

3. **Ecology:** These are taxonomically valuable because even very closely related microorganisms can differ considerably with respect to ecological characteristics. The *ability to cause disease in a particular host*; and *habitat preferences* such as requirements for temperature, pH, oxygen, and osmotic concentration are examples of ecological characteristics.

4. **Genetic analysis:** The study of chromosomal gene exchange between species through transformation and conjugation (in Enteric bacteria) is sometimes useful in their classification. Most bacteria are harboring plasmids, classification based on plasmid is also an important part of classification.

**Molecular characteristics:** This is the most powerful approaches to study taxonomy by analyzing proteins and nucleic acids. Because these are either direct gene products or the genes themselves, comparisons of proteins and nucleic acids yield considerable information about true relatedness.

1. **Comparing amino acid sequences:** Comparison of amino acid sequences of proteins from different organisms reveals its taxonomic relations. The most direct approach is to determine the amino acid sequence of proteins with the same function. If the *sequences* of proteins with the same function are *similar*, the organisms possessing them are *probably closely related*. The *electrophoretic mobility of proteins* is useful in studying relationships at the species and subspecies levels. *Antibodies* can discriminate between very similar proteins, and immunologic techniques are used to compare proteins from different microorganisms.

2. **Nucleic acid composition:** By direct comparison of microbial genomes and based on the G+C content of different organisms (*Escherichia coli* 48-52 %). And genomic fingerprinting (RFLP, AFLP) reveals its relatedness with others.
3. **Nucleic acid hybridization:** It uses the property of complementarities in double stranded DNA. More distantly related organism can be identified based on DNA-RNA hybridization

4. **Nucleic acid sequencing:** Techniques are now available to sequence both DNA and RNA. 5S and 16S RNA (prokaryotes), 18S (fungi) analysis of microorganisms can reveal their relatedness because of its **functional role is same in all ribosomes** and slow structural changes with time.

**Microbial evolution and Diversity**

It has been estimated that our planet is about 4.6 billion years old. Around 3.5 to 3.8 billion years old fossilized remains of prokaryotic cells have been discovered in sedimentary rocks. Thus earlier prokaryotes were anaerobic and arose shortly after the earth cooled. Cyanobacteria and oxygen-producing photosynthesis probably developed 2.5 to 3.0 billion or more years ago. It appears likely that modern eukaryotic cells arose from prokaryotes about 1.4 billion years ago.

**Two hypotheses for the evolution of eukaryotic cells**

1. Organelles arose within prokaryotes from the invagination of the plasma membrane

2. **Endosymbiotic hypothesis**

Fusion of ancient true bacteria and archaia to form a nucleus. They proposed that the eukaryotic line diverged from the *Archaea* and then the nucleus formed, possibly from the Golgi apparatus

Mitochondria and chloroplasts develop later from a permanent symbiotic relationship with other bacteria, e.g., cyanelle (cyanobacterium) living inside the protist *Cyanophora paradoxa*

Cyanobacteria have been considered the most likely ancestors of chloroplasts. More recently *Prochloron* has become the favorite candidate. The existence of this bacterium suggests that chloroplasts arose from a common ancestor of prochlorophytes and cyanobacteria. Mitochondria arose from an endosymbiotic relationship between the free-living primitive eukaryotic and bacteria with aerobic respiration (possibly an ancestor of three modern groups: *Agrobacterium*, *Rhizobium*, and *Rickettsia*).
Divisions of Life

Kingdom systems of classification

-Five-kingdom system (Whittaker, 1960s) - based upon cell type, organization, and the means of nutrient acquisition (Monera, Protista, Fungi, Plantae, Animalia)

-Six-kingdom system - differs from five-kingdom system by dividing prokaryotes into bacteria and archaea (Bacteria, Archaea, Protista, Fungi, Plantae, Animalia)

-Eight-kingdom system (Cavalier-Smith) - further division of the protists using rRNA data and grouping organisms into two empires (Eucaryota and Bacteria) containing a total of eight kingdoms [(Bacteria, Archaea), (Archezoa, Protista, Plantae, Chromista, Fungi, Animalia)]

Domains

Advances in genomic DNA sequencing of the microorganisms, biologists are increasingly adapting the classification of living organisms that recognizes three domains, a taxonomic level higher than kingdom. Archaebacteria are in one domain, eubacteria in a second, and eukaryotes in the third. Domain Eukarya is subdivided into four kingdoms plants, animals, fungi, protists.

Fig. 1 Three domains based on Woese rRNA sequence analysis
**Domain- Archaebacteria**

The term *archaeabacteria* (Greek, archaio, ancient) refers to the ancient origin of this group of bacteria, which seem to have diverged very early from the eubacteria. They are inhabited mostly in extreme environments. The archaebacteria are grouped (based primarily on the environments in which they live) into three general categories methanogens, extremophiles and non extreme Archaebacteria.

![Universal Phylogenetic Tree](image)

**Domain- Bacteria**

The Eubacteria are the most abundant organisms on earth. It plays critical roles like cycling carbon and sulfur. Much of the world’s photosynthesis is carried out by eubacteria. However, certain groups of eubacteria are also responsible for many forms of disease.

**Domain- Eukarya**

It consists of four kingdoms. The first of which is protista, mostly unicellular organism like amoeba. The other three kingdoms are plants, fungi, animals. Multicellularity and sexuality are the two unique characters that differentiate from prokaryote and eukaryotes.
Ways to determine the phylogenetic relationships

Molecular chronometers

This concept, first suggested by Zuckerkandl and Pauling (1965), which is based on thought that the sequences of many rRNAs and proteins gradually change over time without destroying or severely altering their functions. Changes increases with time linearly. If sequences of similar molecules from two organisms differs, it means that they diverged very long time ago.

Phylogenetic tree

Phylogenetic relationships are illustrated in the form of branched diagrams or trees (denrogram). A phylogenetic tree is a graph made of branches that connect nodes. The nodes represent taxonomic units such as species or genes; the external nodes, those at the end of the branches, represent living organisms. The tree may have a time scale, or the length of the branches may represent the number of molecular changes that have taken place between the two nodes. Finally, a tree may be unrooted or rooted.

An unrooted tree simply represents phylogenetic relationships but does not provide an evolutionary path. Figure 3. a. shows that A is more closely related to C than it is to either B or D, but does not specify the common ancestor for the four species or the direction of change. In contrast, the rooted tree Figure 3. b. does give a node that serves as the common ancestor and shows the development of the four species from this root.
**Parsimony analysis**

Phylogenetic relationships also can be estimated by techniques such as parsimony analysis. In this approach, relationships are determined by estimating the minimum number of sequence changes required to give the final sequences being compared. It is presumed that evolutionary change occurs along the shortest pathway with the fewest changes or steps from an ancestor to the organism in question.

**Oligonucleotide signature sequences**

The 16S rRNA of most major phylogenetic groups has one or more characteristic nucleotide sequences called oligonucleotide signatures. Oligonucleotide signature sequences are specific oligonucleotide sequences that occur in most or all members of a particular phylogenetic group. They are rarely or never present in other groups, even closely related ones. Thus signature sequences can be used to place microorganisms in the proper group.

**Polyphasic taxonomy**

Studying phylogeny based on both genotypic and phenotypic information ranging from molecular characteristics to ecological characters.

**Numerical Taxonomy**

Computer based approaches of grouping organisms is called Numerical taxonomy which is based on presence or absence of selected characters in the group of organisms. It is method of estimating percent similarity (ratio between the number of characters same and total number of characters organisms having). This method has great practical usefulness as well as being relatively unbiased in its approach. It has high degree of stability and predictability.

**REFERENCES:**

**Text Books:**


Reference Books:


Module 8 – Diversity of Microbial World

Lecture 2 – Archaea and Bacteria

Archaea

It can be described as, group of (primitive) bacteria living in extreme aquatic and terrestrial environments. They can stain either gram positive or gram negative and may be spherical, rod-shaped, spiral, plate-shaped, or pleomorphic. Some are single cells, whereas others form filaments or aggregates.

They range in diameter from 0.1 to over 15 μm, and some filaments can grow up to 200 μm in length. Multiplication may be by binary fission, budding, fragmentation, or other mechanisms.

Cell walls

Archaeal cell wall is made of glycoprotein or protein instead of peptidoglycan. Methanobacterium and some other methanogens have walls containing pseudomurein, a peptidoglycanlike polymer that has L-amino acids in its cross-links, N-acetyltalosaminuronic acid, and β(1→3) glycosidic bonds Methanosarcina and Halococcus lack pseudomurein and contain complex polysaccharides similar to the chondroitin sulfate of animal connective tissue. Other heteropolysaccharides are also found in gram-positive walls.
Lipids and membranes

This is the most distinctive nature of archaea is membrane lipids. They are different from bacteria and eukaryotes. Archaeal lipids are derivatives of isopranyl glycerol ethers rather than the usual glycerol fatty acid esters. They also contain phospholipids, sulfolipids and glycolipids. Archaeal nonpolar membranes are the derivative of squalene, 30 carbon compound, presence of diethers, tetraethers are needed for their stability to thrive in extreme environments.

Metabolism

Archaeal metabolism varies greatly between the members of different groups. They are just as diverse physiologically. They can be aerobic, facultatively anaerobic, or strictly anaerobic. Nutritionally they range from chemolithoautotrophs to organotrophs. Archaeal carbohydrate metabolism is best understood. The enzyme 6-phosphofructokinase has not been found in archaea, and they do not appear to degrade glucose by way of the Embden-Meyerhof pathway. Extreme halophiles and thermophiles catabolize glucose using a modified form of the Entner-Doudoroff pathway in which the initial intermediates are not phosphorylated. In contrast with glucose degradation, gluconeogenesis proceeds by a reversal of the Embden-Meyerhof pathway in halophiles and methanogens. All archaea that have been studied can oxidize pyruvate to acetyl-CoA. They lack the pyruvate dehydrogenase complex present in eucaryotes and respiratory bacteria and use the enzyme pyruvate oxidoreductase for this purpose. Halophiles and the extreme thermophile Thermoplasma do seem to have a functional tricarboxylic acid cycle.
Archaeal Taxonomy

Based on the rRNA data, it has been divided into two major phylum namely Euryarchaeota, Crenarchaeota. On the basis of morphology and physiology, it has been divided into five different major groups. (1. Methanogenic archaia, 2. Archaea sulfate reducers, 3. Extremely halophilic archaia, 4. Cell wall-less archaia, 5. Extremely thermophilic S₀-metabolizers).

1. Phylum- *Euryarchaeota* (Eures: wide)

The euryarcæota are given this name because they occupy many diverse ecological niches and have a variety of metabolic patterns. It consists of seven classes (*Methanobacteria*, *Methanococci*, *Halobacteria*, *Thermoplasmata*, *Thermococci*, *Archaeglobi*, and *Methanopyri*), nine orders and 15 families.

**Methanogens**

They are strict anaerobes that obtain energy through the conversion of CO₂ and H₂ into methane. This is the largest group of archaea. There are five orders (*Methanobacteriales*, *Methanococcales*, *Methanomicrobiales*, *Methanosarcinales*, and *Methanopyrales*) and 26 genera. Methanogens thrive in anaerobic environments rich in organic matter: the rumen and intestinal system of animals, freshwater and marine sediments, swamps and marshes, hot springs, anaerobic sludge digesters, and even within anaerobic protozoa. Rumen methanogens are so active that a cow can belch 200 to 400 liters of methane a day.

**Halobacteria**

They are aerobic heterotrophs with respiratory metabolism and require complex nutrients, usually proteins and amino acids, for growth. Species are either nonmotile or motile by lophotrichous flagella. The extreme halophiles, class *Halobacteria*, are another major group of archaea, currently with 15 genera in one family, the *Halobacteriaceae*. The most obvious distinguishing trait of this family is its absolute dependence on a high concentration of NaCl. These procaryotes require at least 3 to 4 M NaCl (17 to 23%) for their growth optimum. *Halobacterium* produces energy by trapping light and synthesize ATP with the help of rhodopsin.
Thermoplasms

Thermoacidophiles are the characteristics of lacking cell walls. At present, only two genera, *Thermoplasma* and *Picrophilus*, are known. *Thermoplasma* grows in refuse piles of coal mines. These piles contain large amounts of iron pyrite (FeS), which is oxidized to sulfuric acid by chemolithotrophic bacteria. As a result the piles become very hot and acidic. This is an ideal habitat for *Thermoplasma* since it grows best at 55 to 59°C and pH 1 to 2.

*Picrophilus* is grows at sulfur fields with optimum pH requirement of less than 1. They are aerobic, irregular shaped cocci, having sulfur layer outside its plasma membrane.

Extremely Thermophilic S-Metabolizers

This physiological group contains the class *Thermococci*, with one order, *Thermococcales*. The *Thermococcales* are strictly anaerobic and can reduce sulfur to sulfide. They are motile by flagella and have optimum growth temperatures around 88 to 100°C. The order contains one family and two genera, *Thermococcus* and *Pyrococcus*.

Sulfate-Reducing Archaea

Archaeal sulfate reducers are found in the class *Archaeoglobi* and the order *Archaeoglobales*. This order has only one family and one genus. *Archaeoglobus* contains gram-negative, irregular coccoid cells with walls consisting of glycoprotein subunits. *Archaeoglobus* is extremely thermophilic.

2. Phylum- Crenarchaeota

They are the extreme hyperthermophiles which needs optimum temperature of 105 °C for their growth. At present, the phylum contains 69 genera; two of the better-studied genera are *Thermoproteus* and *Sulfolobus*. *Thermoproteus* is a strict anaerobe and grows at temperatures from 70 to 97°C and pH values between 2.5 and 6.5. It is found in hot springs and other hot aquatic habitats rich in sulfur. *Sulfolobus* are aerobic, with a temperature optimum around 70 to 80°C and a pH optimum of 2 to 3.
**Bacteria**

Bacteria are prokaryotes, evolved first on living earth. They do not contain membrane bound nucleus and organelles. Almost all the bacteria are having circular genome and extrachromosomal DNA which helps in survive different environments. Bacteria reproduce by *prokaryotic fission*, resulting in two genetically identical daughter cells. Most of the bacteria are unicellular in nature but sometimes they form aggregates. The most common shapes of bacteria are spheres (cocci), rods (bacilli), spirals.

Bacterial cell walls are made of peptidoglycan contains sugar moieties (N-acetylglucosamine, and N-acetylmuramic acid cross linked with pentapeptide (D-aminoacids). Gram stain is a valuable tool to identify the bacteria based on the cell wall constituents. **Gram-positive** bacteria have simple cell walls with large amounts of peptidoglycan and which retains crystal violet. **Gram-negative** bacteria have more complex cell walls with less peptidoglycan and which retains saffron, the counter strain. Presence of lipid layer is a unique characteristic of Gram negative bacteria. Most of the gram negative bacteria are causative agent of many human diseases than Gram positive bacteria. The lipopolysaccharides on the walls of gram-negative bacteria are often toxic, and the outer membrane protects the pathogens from the defenses of their hosts.

Capsules are the slimy layer produced by most of the bacteria which helps them to adhere together and form colonies. Two kinds of filamentous structures may be attached to the cell wall: The bacterial flagellum rotates like a propeller to pull the cell along while movement. Pili help bacteria attach to one another in conjugation, and fimbriae help them attach to surfaces. Many prokaryotes are capable of *taxis*, movement toward nutrients or oxygen (positive chemotaxis) away from a toxic substance (negative chemotaxis). Some bacteria form resistant cells called *endospores* when an essential nutrient is lacking in the environment and it may remain dormant but viable for centuries or longer.
Classification based on nutrition and metabolism

Organisms can be categorized by their nutrition, based on how they obtain energy and carbon to build the organic molecules that make up their cells. Organisms that obtain energy from light are phototrophs. Organisms that obtain energy from chemicals in their environment are chemotrophs. Organisms that need only an inorganic compound such as CO2 as a carbon source are autotrophs. Organisms that require at least one organic nutrient—such as glucose—as a carbon source are heterotrophs. Based on requirement of oxygen they are classified as obligate aerobes (requires O2 for respiration), facultative anaerobes (can grow both aerobically and anerobically), and obligate anaerobes (does not require O2).

Bacterial taxonomy

Until the late 20th century, biologists based prokaryotic taxonomy on criteria such as shape, motility, nutritional mode, and Gram staining. Although these criteria may be valuable in culturing and identifying pathogenic bacteria, they may not reflect evolutionary relationships. Applying molecular data to the investigation of prokaryotic phylogeny has been very fruitful. Microbiologists began comparing sequences of prokaryotic genes in the 1970s. Carl Woese and his colleagues used ribosomal RNA (rRNA) as a marker for evolutionary relationships.

In 1923, David Bergey and colleagues set out to publish a definitive book on the identification and classification of bacteria. A Survey of Bacterial Phylogeny and Diversity - based on the 2nd edition of Bergey's

Volume 1: The Archaea, Cyanobacteria, Phototrophs and Deeply Branching Genera

Archaea - divided into two kingdoms
a. Crenarchaeota - diverse kingdom that contains thermophilic and hyperthermophilic 
b. Euryarchaeota - contains primarily methanogenic and halophilic bacteria and also

Eubacteria - complex with several small groups of phototrophs, cyanobacteria, and deeply branching eubacteria
Based on Bergeys’ manual Domain Bacteria contains six phyla in volume 1

- Phylum *Aquificiae* - earliest branch of bacteria that contain autotrophs which utilize hydrogen for energy production
- Phylum *Thermotogae* - anaerobic, thermophilic, and fermentative Gram negative bacteria
- Phylum “Deinococcus Thermus” - radiation resistant bacteria
- Phylum *Chloroflexi* - green non-sulfur bacteria that carries out anoxygenic photosynthesis
- Phylum *Cyanobacteria* - oxygenic photosynthetic bacteria
- Phylum *Chlorobi* - green sulfur bacteria that carry out anoxygenic photosynthesis

**Volume 2 - Gram negative proteobacteria (purple bacteria)**

Based on the nutritional type and rRNA data Gram negative- *Proteobacteria* have been classified into five classes.

- *Alphaproteobacteria* - oligotrophic forms including the purple nonsulfur photosynthesizers
- *Betaproteobacteria* - metabolically similar to alphaproteobacteria
- *Gammaproteobacteria* - diverse methods of energy metabolism
- *Deltaproteobacteria* - includes predators and the fruiting myxobacteria
- *Epsilonproteobacteria* - contains pathogens

**Volume 3 - Gram positive bacteria with low G + C content (< 50%)**

Three classes of the phylum *Firmicutes*

- *Clostridia* - tend to be anaerobic and endospore formers
- *Mollicutes* - mycoplasmas (no cell walls)
- *Bacilli* - Gram-positive aerobes or facultative anaerobes, rods or cocci, some endospore formers

**Volume 4 - Gram positive bacteria with high G + C content (> 50-55%)**

- All belong to the phylum *Actinobacteria*
- Some are filamentous
Volume 5 - Gram negative with various morphologies

Nine phyla of which four are presented below

- Phylum *Planctomycetes* - some have a membrane-bound nucleus
- Phylum *Chlamydiae* - obligate intracellular parasites important in disease
- Phylum *Spirochaetes* - helical-shaped, Gram-negative motile bacteria (axial filaments)
- Phylum *Bacteroidetes* - ecologically significant species are found in this phylum

REFERENCES:

Text Books:


Reference Books:


Module 8 – Diversity of Microbial World
Lecture 3 – Fungi, algae, protozoa and slime molds

Fungi

Basic features:

It belongs to the domain Eukarya. They are unicellular (yeast) as well as multicellular organism (filamentous fungi). Multicellular fungi are composed of filaments called hyphae (singular: hypha). Hyphae may contain internal cross walls, called septa, which divide the hyphae into separate cells. The hyphae may be branched. A mass of hyphae that is not a reproductive structure is called a mycelium. Fungi are saprophytic; absorb nutrients after degrading the organic matter and heterotrophs; require organic compounds. They have cell walls composed of chitin. The hyphae of some symbiotic fungi become specialized for penetrating the cells of the host. These hyphae are called haustoria. Reproduce both sexually and asexually, typically through the production of spores. Sexually produced spores are resting spores. In general, the life cycle involves the fusion of hyphae from two individuals, forming a mycelium that contains haploid nuclei of both individuals. The fusion of hyphae is called plasmogamy. The fused hyphae containing haploid nuclei from two individuals are heterokaryotic. In some cases, plasmogamy results in cells with one nucleus from each individual. This condition is called dikaryotic. It has been classified based on the mode of reproduction

- Lower fungi-

  Fungi belongs to this family are having nonseptate walls and spores contained in small sporangia. These classes of fungi include three groups: Chytridiomycota, Oomycota, Myxomycota

- Higher fungi - true fungi (Kingdom Fungi)

  Fungi belongs to this family are having septate cross walls spores contained in complex structures
  Include three groups: Zygomycota, Ascomycota, Basidiomycota
Asexual Spores
Produced by mitosis and cell division

1. Sporangiospore
   - Spores form sac called sporangium
   - Sporangium forms at end of aerial hyphae called a sporangiophore. Hundreds of sporangiospores in a single sporangium

2. Conidiospore
   - Spores produced at the end of an aerial hyphae is called as conidiophore
   - Conidia: chains of conidiospores on conidiophores

Sexual Spores
Sexual spores formed by fusion of two haploid nuclei into single diploid zygote. zygote then undergoes meiosis to generate haploid spores (usually multiples of four)

1. Zygospores
   - One thick spore between two parent hyphae

2. Ascospores
   - Four spores in a sac called an ascus, at the end of one hyphae

3. Basidiospores
   - Four spores on the end of a basidium

Fungi organized into three Phyla based on the type of sexual spore:

**Phylum Chytridiomycota (chytrids or water molds)**

Basic features:

- Aquatic, unicellular and coenocytic (multinucleate), hyphae are typically haploid (but some diploid) - typically composed of a microscopic sphere, cell walls are made of chitin.
- They have Rhizoids to penetrate food source. Many are parasitic on plants and other fungi. Some are saprophytics.

Reproduction:

- Asexual reproduction - *Sporangium* with single nucleus that splits off to produce a flagellate zoospore with one flagellum. Sexual production through the formation of sporophyte.
Phylum Oomycota (water molds & mildews)

Basic features:
Aquatic, extensive nonseptate mycelium (unicellular, coenocytic), hyphae are diploid, cell walls made of cellulose, they are heterotrophic: parasites on fish, plant pathogen, also initial decomposers of dead insects.

Asexual Reproduction:
Hyphae grow, terminal portions of a mycelium pinch off to produce Zoospores, each with two flagella.

Sexual Reproduction
Reproductive cells produced by meiosis several eggs per Oogonium, Antheridium long and skinny (clavate).

Phylum Myxomycota (plasmodial slime molds)

Basic features:
They are terrestrial; contain no cell walls, vegetative structure are called as plasmodium which is diploid (coenocytic), Amoeboid-feed by phagocytosis.
With adverse environmental conditions (ex. drought)-formation of a hardened Sclerotium (multicellular resting structure)

Sexual Reproduction
Sporangium development -- meiosis to form 4 haploid spores, 3 of the 4 spores disintegrate before release. Germination into amoeboid cells, some cells become flagellate, fusion to form a zygote which later develops into a new plasmodium

Phylum Zygomycota (pin and bread molds)

Basic features:
Terrestrial, hyphae haploid, septate, cell walls made of chitin
Saprophytic
Produced complex reproductive structure; zygosporangium with one zygospore
Asexual Reproduction:
- Nonmotile spores on aerial sporangia
- Spores are air dispersed

Sexual Reproduction
- When two hyphae come in contact, they produce Gametangia by the initiation of process of conjugation (fusion), and two haploid nuclei into a common cell and fertilize with a thickened wall; *Zygosporangium*

**Phylum Ascomycota (cup or sac fungi)**
Include: morels, truffles, yeasts, dutch elm disease, corn blight

Basic features:
- Hyphae are septate and monokaryotic (having one nucleus per compartment)
- Produce complete reproductive structure called ascocarp with 8 ascospores

Asexual Reproduction:
- Produce a sporangium-like conidium, within it called as conidiospores
- Some species - no sexual reproduction seen, produce only conidia:
  a) *Penicillium* - flavoring in cheese (blue, Roquefort, Camembert)
  b) *Aspergillus* - aid in fermentation of soybean to produce Tofu

Sexual Reproduction

Hypal fusion leads to production of dikaryotic cells which in turn form into ascocarp. and through meiosis it produces 8 ascospores.

Three types of sporocarps:
- 1) Apothecium - most common, cup fungi, morels
- 2) Perithecium - small flask-shape with small opening
- 3) Cleistothecium - no opening, release by decomposition

**Yeast**s: most common *Saccharomyces*

Yeast are single celled having diploid nucleus, mostly reproduce asexually by budding
Sexual reproduction through meiosis to from 4 ascospores.
**Phylum Basidiomycota** (club fungi)
Include: mushrooms, coral fungi, rusts, smuts

Basic features:
- Mainly terrestrial
- Hyphae are septate and monokaryotic (having one nucleus per compartment)
- Produce complete reproductive structure called *basidiocarp* with 4 basidiospores

**Sexual Reproduction**
- Sexual process similar to that of ascomycetes
- Fusion to get dikaryotic mycelia which develop into sporocarp-*Basidiocarp*
- Immediate meiosis to form 4 Basidiospores on a *Basidium* (club-like structure)

**Symbiosis Involving Fungi**

Two types involving fungi:
1) mutualism - both species benefit
2) parasitism - one benefits, one harmed

**Mutualism**
- Two examples: mycorrhizae & lichens

**Mycorrhizae** are the result of fungi in the roots of vascular plants
- Fungus benefits: obtains photosynthates (esp.: sugar)
- Plant benefits: obtains minerals (esp.: N, P)

Two types of mycorrhizae based on type of infection

1) Ectomycorrhizae (sheathing)
   - Grow between root cells of epidermis & cortex, not into cells, not beyond endodermis
   - results in short, stubby roots
   - most common in: conifers, oaks, willows which are infected with basidiomycetes.
2) Endomycorrhizae (internal)

Fungal hyphae grow into root cells
Within cell walls, NOT cell membrane
Mainly in epidermal & cortex cells
Most common in angiosperms (ex.: tulip tree) which are infected by zygomycetes

Lichens are the result of a fungus and an algae living together

a) The mycobiont - a fungus
   Mostly ascomycetes, but some basidiomycetes
   Provides a suitable environment & minerals to algae
b) The photobiont - an algae
   An algae (green) or cyanobacterium
   Provide carbohydrate & nitrogen compounds to fungus
   Symbiosis allows for them to live in very harsh environments: rock surfaces, tree trunks
   Ability to survive related to ability to dehydrate quickly
   Fungal surface blocks UV light

Algae

Algae are photoautotrophic, unicellular (colony) as well as multicellular (filamentous).
Cell walls are made of cellulose or pectin, and require high moisture for their growth.
Reproduction is through sexual as well as asexual.

Five phyla

1. Brown algae
   They are dark pigment producing, non motile multicellular organism, contains chlorophyll a and b. *Example.* Sea weed.

2. Red alage
   They are red pigment producing, non motile multicellular organism, contains chlorophyll a and d. *Example-* Sea weed.
3. **Green Algae**

They are filamentous unicellular as well as multicellular organisms, contains chlorophyll a and b.

Example- Pond scum

4. **Diatoms**

They are light brown pigment producing unicellular organisms. Cell wall is made of pectin and silicon oxide.

5. **Dinoflagellates**

They are unicellular, flagellated organisms. Their cellulose walls are interlocked.

*Example*- Plankton, red tide

**Protozoa**

Most of the protozoa are unicellular, aerobic, and chemoheterotrophic in nature. Reproduction is through sexual as well as asexually. They also require high moisture for their growth as algae. They have specialized structures to take food. Protozoa usually covered with pellicle. Digestion occurs in vacuoles. Their life cycle switch between two forms; one is trophozoite (vegetative and growing stage), and another one is cyst stage. This is the survival stage for protozoa where they will move from one host to another, resisting to the different environmental conditions. Cyst will turn back to their vegetative stage when it finds favorable conditions.

Based on gene sequencing and motility it has been grouped into five major phyla

1. **Archaeaoa**

Archaeaoa are spindle shaped, lack mitochondria. They are having flagella at the front end and common symbionts in animal. Example- *Giardia*

2. **Apicomplexa**

Organisms present in this groups are obligate intracellular parasites, and non motile in mature form. Usually transmitted by insects, and having complex life cycle with different stages in different hosts. Example- *Plasmodioium* (malaria)

3. **Amoebozoa**

This group contains causative agent of dysentery, and they move with the help of pseudopods. Example- *Entamoeba*
4. **Ciliophora**

Only one pathogen in group called *Balantium coli*, which is also a causative agent of dysentery. They move with the help of cilia present on the surface of cell. Example: *Paramacium*.

5. **Euglenozoa**

Asexual mode of reproduction and movement with the help of flagella called zooflagellates. It contains two groups; a) *Euglenoids*: they are photoautotroph as well as chemoautotrophs, has chlorophyll a, movement via flagella, b) *Hemoflagellates*: they are long slender cells with undulating membrane and flagellum. Transmitted through insects and live in host blood as the name implies. Example: *Trypansoma*

**Slime Molds**

They are having both the properties of fungi and amoeba, and mostly related to amoebazoa. They are the parasites of bacteria and fungi and produce spores in unfavorable conditions. It has been divided into two phyla; cellular slime molds and plasmodial slime molds.

1. **Cellular slime molds**

In favorable conditions, they exist as unicellular amoeba and in unfavorable conditions; they form as aggregate of multicellular mushroom like structure to generate spores. When return to favorable conditions, spores germinate into unicellular amoeba.

2. **Plasmodial slime molds**

In favorable conditions, they exist as plasmodium containing multinucleated mass of protoplasm. They used to adapt amoeba like movement. In unfavorable conditions, they form into mycelium, which in turn produces spores on aerial hyphae. When it returns to the favorable conditions, spores germinate and undergo rapid cell division to form new plasmodium.
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