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FERHAT ABBAS UNIVERSITY SETIF 1

Université Ferhat ABBAS Sétif 1

Faculty of Natural and Life Sciences

Department of Agricultural Sciences

Cell Biology Course

For students "First year"

Bachelor's Degree in Agricultural Science

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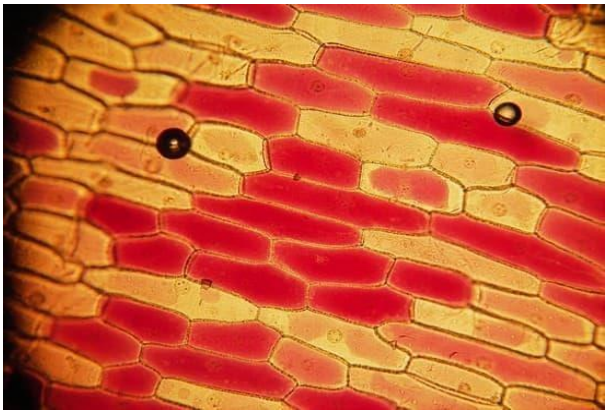

Academic Year 2025-2026

List of abbreviations

DNA: Deoxyribonucleic Acids

RNA : Ribonucleic Acid

rRNA : Ribosomal RNA

mRNA : pre-messenger RNA

tRNA : transfer RNA

ER : Endoplasmic Reticulum

AG : Golgi Apparatus

ATP: Adénosine Triphosphate

ADP : Adénosine Diphosphate

GPI : Phosphatidyl-inositol group,

ATPASE : Adénosine Triphosphatase

GTP : Guanosine Triphosphatase

REG : Granular Endoplasmic Reticulum

RER : Rough Endoplasmic Reticulum,

REL : Smooth Endoplasmic Reticulum

(A): Adenine

(T): Thymine

(U): Uracil

(C): Cytosine

(G): Guanine

LDL: Low Density lipoproteins

PTP: Rermeability Transition Pore

NADPH: Nicotinamide Adenine Dinucleotide Phosphate

PS: Photosystems

APG molecule: 3-Phosphoglyceric Acid

PGA : phosphoglycerate

ECM: Extracellular Matrix

GAGs : Glycosaminoglycans

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General introduction

Cell biology is a central discipline in the life sciences. It focuses on the study of cells, which are considered to be the basic structural and functional units of all living organisms. Whether bacteria, animals, plants or fungi, all organisms are made up of cells, which perform all the functions necessary for life: nutrition, reproduction, communication, adaptation, etc.

The emergence of cell biology dates back several centuries, but it was in the 19th century that cell theory was formulated, stating that all living beings are composed of cells, and that every cell comes from another cell. Since then, technological advances, particularly in microscopy and molecular biology, have led to a better understanding of the structure and functioning of cells, as well as their interactions within organisms.

This course aims to provide the essential foundations for understanding how cells are organised, how they function, how they reproduce and how they communicate with each other. This knowledge is fundamental not only to biology, but also to applied fields such as biotechnology and agricultural science research, including plant and animal breeding.

This cell biology course, intended for first-year university students, is organised into three main parts. The first part presents general information about cells, focusing on different cell types, the principles of cell theory and the major stages of cell evolution. The second part is devoted to the methods used to study cells in order to better understand their structure and functions. Finally, the third part provides a detailed description of the main cellular components, explaining their organisation, role and importance in the overall functioning of the cell.

1. General information

Cell biology, also known as cytology, is biology applied to cells. Cytology (from the Greek 'kutos' = 'cell' and "logos" = 'discourse') is the study of the structure and physiology of cells in general, regardless of their origin (animal, plant, etc.) and function.

It was in 1665 that botanist Robert Hooke (1635–1702) discovered the cell (from the Latin 'cellula' = 'small chamber'). The alveolar structures observed in thin slices of cork and then in other plant tissues were mainly the cellulosic cell walls of sometimes dead cell skeletons.

At the same time, Anthony van Leeuwenhoek (1632-1723), improving the quality of the microscope lens (50 to 300X) that appeared in Holland around 1590, observed animal cells for the first time: among others, those of blood and muscle tissue, spermatozoa, and even bacteria in his mouth.

1.1. Classification and relative importance of kingdoms

The kingdom (from the Latin 'regnum') is, in classical taxonomies of biodiversity based on shared common characteristics, the highest level of classification of living beings.

Linnaeus' traditional classification (1735) into two groups (plant/animal) has evolved to become the six kingdoms (Cavalier-Smith) of life according to biology:

• **Archaea,** or formally ***Archea*** (unicellular prokaryotes with histones and the first unicellular organisms to appear 3 billion years ago);

• **Bacteria**, or formally ***Bacteria*** (unicellular prokaryotes without histones);

• **Protists** or formally ***Protista*** (unicellular eukaryotes), divided into protozoa (or formally Protozoa) and chromists (or formally Chromista, including brown algae);

• **Plants** or formally ***Plantae*** (multicellular eukaryotes with a vacuole, also including green algae).

• **fungi**, or formally ***Fungi***, commonly known as mushrooms (mostly multicellular eukaryotes, but some are unicellular, heterotrophic and osmotrophic);

• **animals,** or formally ***Animalia*** (multicellular eukaryotes).

The numerical importance of the different kingdoms of the living world is as follows: - Animalia: - Plantae - Protista (protophytes-protozoa); - Fungi ; - Monera (Archaebacteria-Eubacteria) Among animals: Arthropods and molluscs are the two most important phyla.

1.2. Cells and cell theory

In 1665, Robert Hooke discovered cells in cork, then in living plants, using a microscope (inventor of the term 'cell'). In 1838, Matthias Schleiden suggested that all plant tissues are made up of cells. In 1839, Theodor Schwann came to the same conclusion about animals (cell theory). In 1855, Rudolf Virchow suggested that all cells originate from other cells.

Mathias Schleiden (in 1838; German botanist) and Theodor Schwann (in 1839; German zoologist) concluded that plants and animals have a similar structure and proposed that:

• **All organisms are composed of one or more cells.**

• **The cell is the structural unit of life**.

In 1958, Rudolf Virchow (German pathologist) formulated the third principle of cell theory: **Cells can only arise from the division of a pre-existing cell**.

In summary, the observations and discoveries of these scientists led to the establishment of the cellular theory proposed in the 18th century, which comprises three main principles:

• **All living beings are composed of one or more cells.**

• **The cell is the basic unit of life.**

• **Every cell originates from another cell through cell division**.

During its cycle, the cell undergoes two major phases: a functional phase (**interphase**) and a multiplication phase **(mitosis**).

- **Interphase**

Interphase is the period of the cell cycle during which the cell is not dividing. It precedes mitosis and consists of three phases: G1 (cell growth), S (DNA replication) and G2 (preparation for division). During interphase, the cell performs its normal functions, doubles its DNA content and prepares to divide.

- **Mitosis**

Mitosis is the process of division of the nucleus of a eukaryotic cell, which allows two identical daughter cells to be formed, possessing the same genetic material as the mother cell. It takes place in several successive stages: prophase, metaphase, anaphase and telophase, and is followed by cytokinesis, which divides the cytoplasm.

1.3. Origin and evolution

1.3.1. Origin of life and appearance of the first cells

Around 3.8 to 4 billion years ago, life is thought to have appeared in conditions very different from those of today, on the primitive Earth (rich in volcanoes, warm seas, oxygen-free atmosphere).

There are two main hypotheses explaining the origin of the first biological molecules (RNA, proteins, lipids):

• **Chemosynthetic hypothesis** (or prebiotic soup): simple organic molecules formed spontaneously in the ocean under the influence of energy (lightning, UV rays, heat).

• **Hydrothermal vent hypothesis**: underwater volcanic vents provided the energy and conditions conducive to the formation of the first complex molecules.

1.3.2. The first cells: protobionts, then prokaryotes

• **Protobionts** were primitive structures surrounded by a lipid membrane, capable of self-organisation and simple chemical reactions.

• These structures gave rise **to prokaryotic cells** (without a nucleus), **primitive bacteria**, around 3.5 billion years ago.

• **RNA** is thought to have played a central role in the earliest forms of life (**RNA world hypothesis**), before being replaced by DNA as the main carrier of genetic information.

1.3.3. The emergence of eukaryotic cells: the endosymbiosis theory

Around 2 billion years ago, more complex prokaryotic cells gave rise to eukaryotes (cells with a nucleus).

The endosymbiosis theory (formulated by Lynn Margulis) explains this as follows:

• A prokaryotic cell engulfed (by phagocytosis) other bacteria without digesting them.

• Some of these bacteria remained alive inside, establishing a symbiotic relationship.

• These internal bacteria became:

- ✓ mitochondria (from aerobic bacteria),
- ✓ Then, in plants, chloroplasts (from photosynthetic cyanobacteria).

1.3.4. Cellular diversification

Over time, eukaryotic cells evolved into:

• Complex single-celled organisms (protozoa, algae, yeasts),

• Then multicellular organisms (plants, animals, fungi).

The specialisation of cells led to the emergence of tissues, organs, and a wide variety of living beings.

1.4. Cell types (prokaryotes, eukaryotes, acaryotes)

1.4.1. The prokaryotic cell

Prokaryotes: from the Greek pro: before and karyon: nucleus. Prokaryotes are single-celled organisms without a nucleus or membrane-bound organelles.

These single-celled organisms are characterised by:

- ✓ ***Absence of a nucleus***: DNA is free in the cytoplasm, grouped together in a region called the nucleoid.
- ✓ ***Their size***: which varies from 1 to 10 µm.
- ✓ ***The presence of a single circular chromosome***.
- ✓ ***No membrane-bound organelles*** (no mitochondria, Golgi apparatus, etc.).
- ✓ ***Asexual reproduction***: by scissiparity (binary division): therefore, there is no mitosis or meiosis.
- ✓ ***Rigid cell wall*** (in most cases), composed of peptidoglycan (in bacteria).

The prokaryotic cell consists of (Figure 01):

- ✓ **a homogeneous cytoplasm**, bounded by a plasma membrane.
- ✓ **a nucleoid**: equivalent to the nucleus: a single circular DNA molecule 1 mm in length: the bacterial chromosome. It is not surrounded by an envelope separating it from the cytoplasm.
- ✓ **plasmids**: these are circular extrachromosomal DNA fragments located in the cytoplasm.
- ✓ **ribosomes:** visible in the cytoplasm, most often grouped into polyribosomes.
- ✓ **A plasma membrane**: composed of lipids and proteins and low in carbohydrates.

- ✓ **A mesosome**: not a real functional structure of the bacterial cell, but an observation artifact
- ✓ **A flagellum**: a mobile membrane expansion, of which there are between 1 and 8.
- ✓ **Pili (hairs)**: membrane expansions that are shorter than flagella, useful for adhesion.
- ✓ **a capsule**: inconsistent, it is polysaccharidic in nature, amorphous, often very thin

Examples : Bacteria, Archaea

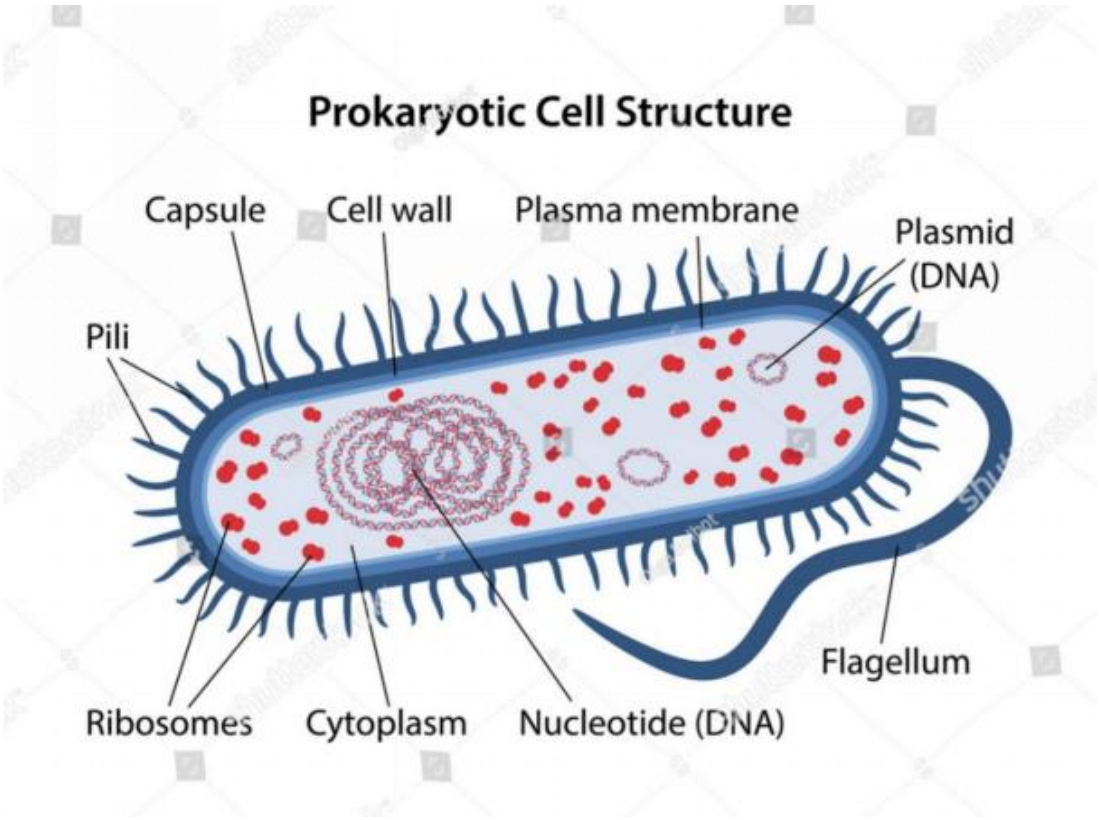

Figure 01: The prokaryotic cell

REMARK

Bacterial identification by GRAM staining

Gram staining is named after Danish bacteriologist Hans Christian Gram, who developed the protocol in 1884. It is the most widely used staining method in bacteriology and highlights

differences in the nature of the bacterial cell wall: ***Gram-positive bacteria and Gram-negative bacteria:***

- **Gram-positive bacteria** retain the dye, staining purple. Their cell walls have a single homogeneous layer of peptidoglycan, called ***murein***, which rests on the plasma membrane; together, these two components form the cell wall. Example: staphylococci (Figure 02)

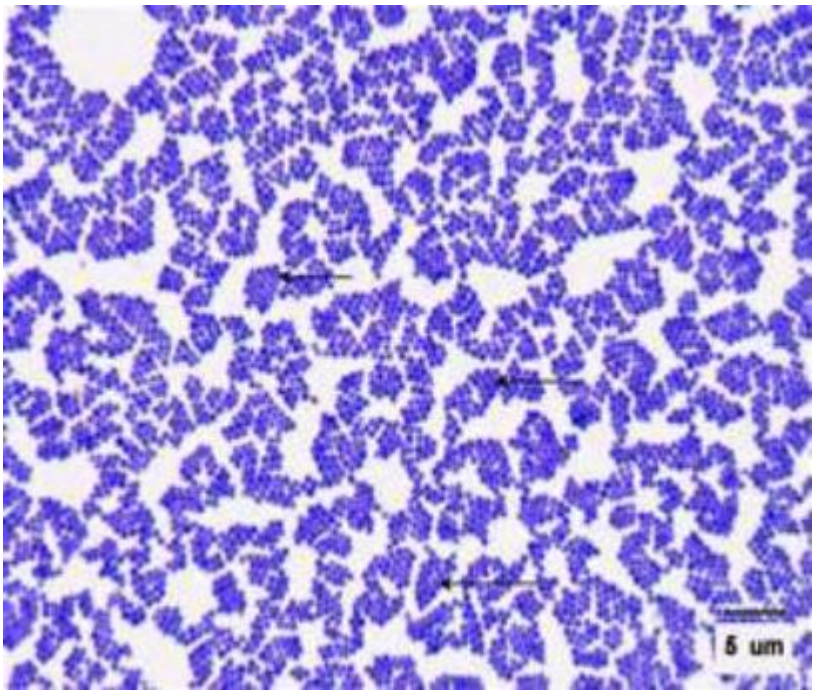

Figure 02: Microscopic observation of Gram + bacteria (Staphylococcus)

• Gram-negative bacteria – are much more permeable to dye, staining pink. Their walls are much more complex and consist of a thin layer of peptidoglycans that rests on the plasma membrane surrounded by an outer membrane. Example: Escherichia coli (Figure 03)

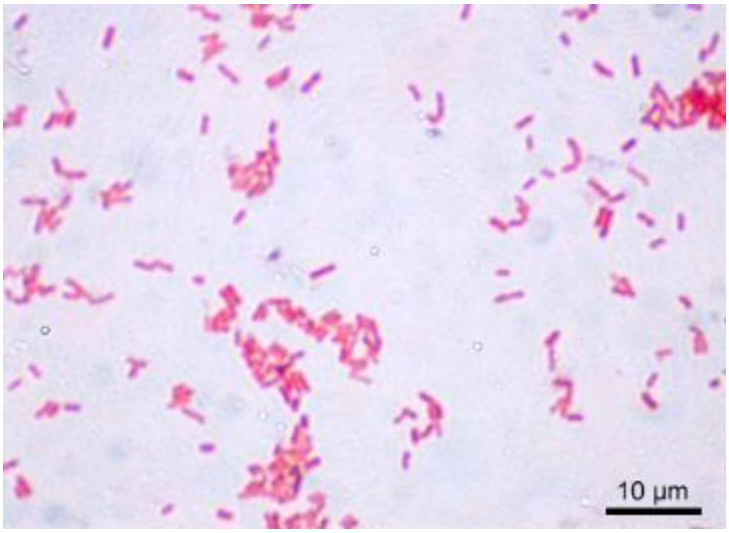

Figure 03: Microscopic observation of Gram – bacteria (E. coli)

In summary, Gram-negative bacteria have a thinner peptidoglycan layer than Gram-positive bacteria (Figure 04).

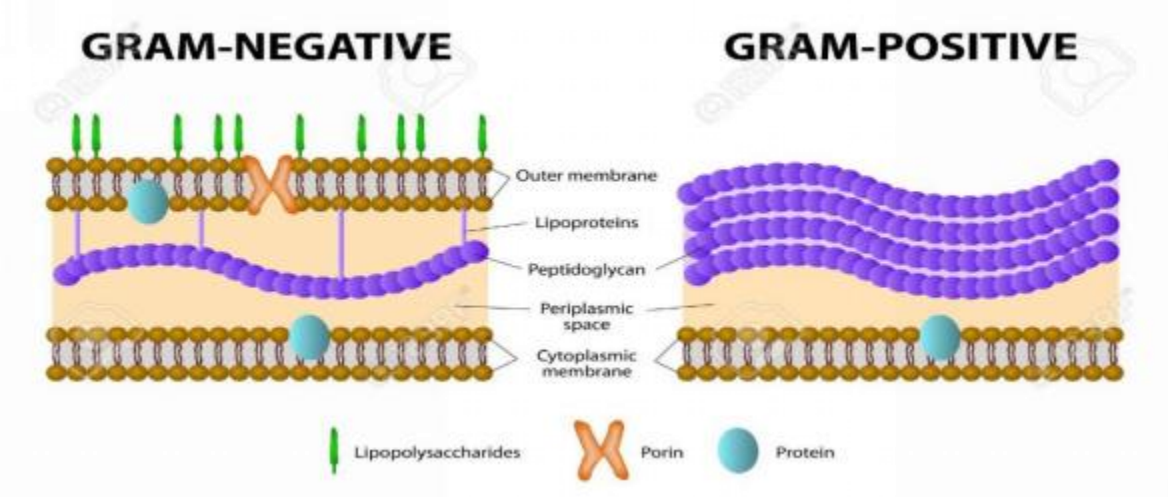

Figure 04: Structural difference between the cell walls of Gram-positive and Gram-negative bacteria.

Gram-positive bacteria have a thick cell wall consisting of a layer rich in peptidoglycan and containing teichoic acids, but do not have an outer membrane. They retain the violet dye during Gram staining.

Gram-negative bacteria, on the other hand, have a thin cell wall with little peptidoglycan, located between two membranes. They have an outer membrane containing lipopolysaccharides (LPS), which are responsible for their toxicity. They appear pink after Gram staining because they do not retain the violet dye.

1.4.2. The Eukaryotic Cell

The term eukaryote means "***true nucleus***." Among eukaryotes, we have plant and animal cells. Eukaryotic cells (Figure 5) contain large membrane surfaces, delimiting several organelles such as the nucleus, mitochondria, ER, AG, lysosomes, peroxisomes, chloroplasts, and vacuoles. All cellular functions are compartmentalized and carried out by specialized structures, each surrounded by a membrane.

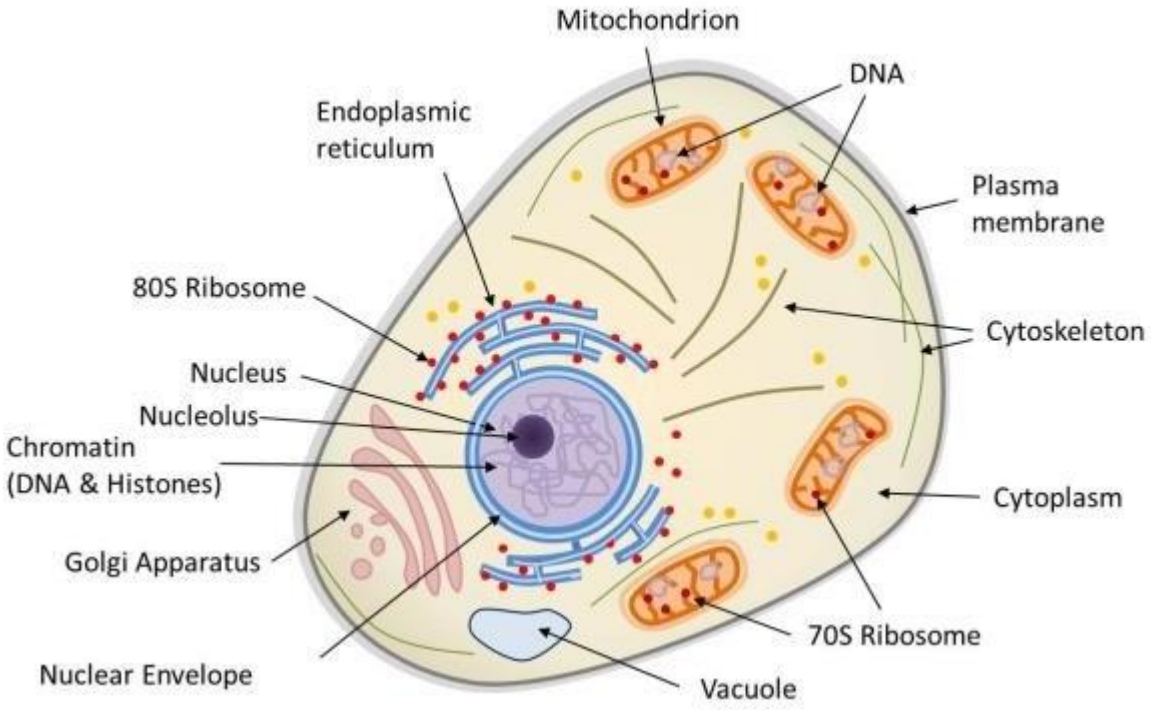

Figure 5: The Eukaryotic Cell

• ***Diversity and common characteristics between prokaryotes and eukaryotes***

Prokaryotic cells do not contain organelles. In eukaryotic cells, however, all functions are performed by a specific type of organelle. Each organelle is surrounded by a membrane. The internal composition of each organelle depends on its function. Prokaryotes and eukaryotes have similar plasma membrane structures. Genetic information is encoded in DNA using an identical genetic code, with similar mechanisms for transcription and translation of genetic information. Another common feature is the same mechanism for storing chemical energy in the form of ATP (located in the plasma membrane of prokaryotes and in the mitochondrial membrane of eukaryotes).

Eukaryotic and prokaryotic cells differ in several fundamental characteristics. Eukaryotes have a nucleus enclosed by a nuclear envelope, whereas prokaryotes do not, their genetic material being free in the cytoplasm. Eukaryotes also have membrane-bound organelles (mitochondria, endoplasmic reticulum, Golgi apparatus, etc.), which are absent in prokaryotes. Cell size is generally larger in eukaryotes (10 to 100 µm) than in prokaryotes (1 to 10 µm). In terms of reproduction, eukaryotes can divide by mitosis or meiosis, while prokaryotes divide mainly by binary fission. Finally, although simpler, prokaryotes show great metabolic diversity and a capacity for rapid adaptation, particularly through horizontal gene transfer.

The table 01 summarises the main points of comparison between prokaryotic and eukaryotic organisms.

Table 01: Comparison between prokaryotes and eukaryotes

Definitions / Description	Eukaryotic Cell	Prokaryotic Cell
Organisms:	Plants, animals and fungi have eukaryotic cells.	Only bacteria and cyanobacteria have prokaryotic cells.
Cell wall:	No (animals); Yes (plants)	Yes
Centrioles:	Yes (all animals and some lower plant forms)	No
Cilia and Flagella:	Yes, simple	Yes, complex
Golgi Complex:	Yes	No
Lysosomes:	Common in animals; Not present in plants	No
Peroxisomes:	Yes	No
Nucleus:	Yes	No
Plasma membrane:	Yes	Yes
Chromosomes:	Several chromosomes	One long DNA strand
Ribosomes:	Yes	Yes
Endoplasmic Reticulum:	Present	Absent

1.4.3. Acaryotic cell (Virus)

A virus is a biological entity incapable of reproducing independently, requiring a host cell, whose components it uses to multiply. In 1883, Adolf MAYER described tobacco mosaic disease (a viral disease) (mosaics and discolouration of tobacco leaves).

In 1892, Dimitri IVANOVSKI discovered that the filtering pathogens of tobacco mosaic were not bacteria (extract from diseased tobacco leaves remained infectious after filtration through a Chamberland filter, which retained bacteria).

In 1898, Martinus BEIJERINCK proposed the name Virus for the agent causing tobacco mosaic disease.

In 1953, André LWOFF proposed a definition of viruses: vital structures containing neither cytoplasm nor nucleus (acellular structure or particle), containing only one type of nucleic acid: DNA or RNA. They are obligate parasites (they possess genetic information but neither the DNA transcription system nor the mRNA translation system).

The virus exists in two forms:

- ✓ ***Intracellular***: (inside the prokaryotic or eukaryotic host cell): the viral genetic material replicates and controls the synthesis of specifically viral proteins.
- ✓ ***Extracellular***: isolated, showing no vital activity.

Viruses are elements containing **nucleic acid** (DNA or RNA, single or double stranded) in the form of a filament stabilised by basic nucleoproteins (the seat of genetic information). They have a compact protective structure to protect the nucleic acid, called **a capsid**, and are sometimes surrounded by **an envelope**. ***The free form of the virus (viral particle) is called a virion.***

The viral genome can be DNA or RNA. It represents the viral genome (composed of a few genes to 1,200 genes). It can be circular or linear, single-stranded (single strand) or double-stranded (double strand).

The capsid is a shell that surrounds and protects the viral nucleic acid from various attacks from the external environment or the cytoplasmic environment of the host cell. It accounts for most of the virus's mass and is responsible for its crystalline appearance under an electron microscope. This shell is made up of an assembly of protein structures.

The capsid and nucleic acid together are called **the nucleocapsid**.

The structure of the capsid defines the shape of the virus, which allows us to distinguish between two main groups of viruses:

- ✓ viruses with cubic or icosahedral symmetry.

- ✓ viruses with helical symmetry.

Many viruses are surrounded by an envelope. This envelope has a complex structure made up of phospholipids and proteins. It carries viral determinants (glycoproteins) that bind specifically to cell receptors, allowing the nucleocapsid to enter the host cell.

There are two types:

- ✓ ***Naked viruses***, which do not have an envelope. Example: the polio virus (picovirus) (figure 06).
- ✓ ***Enveloped viruses***, which have an envelope. E.g.: influenza virus (orthomyxoviridae) and AIDS virus (retroviridae family).

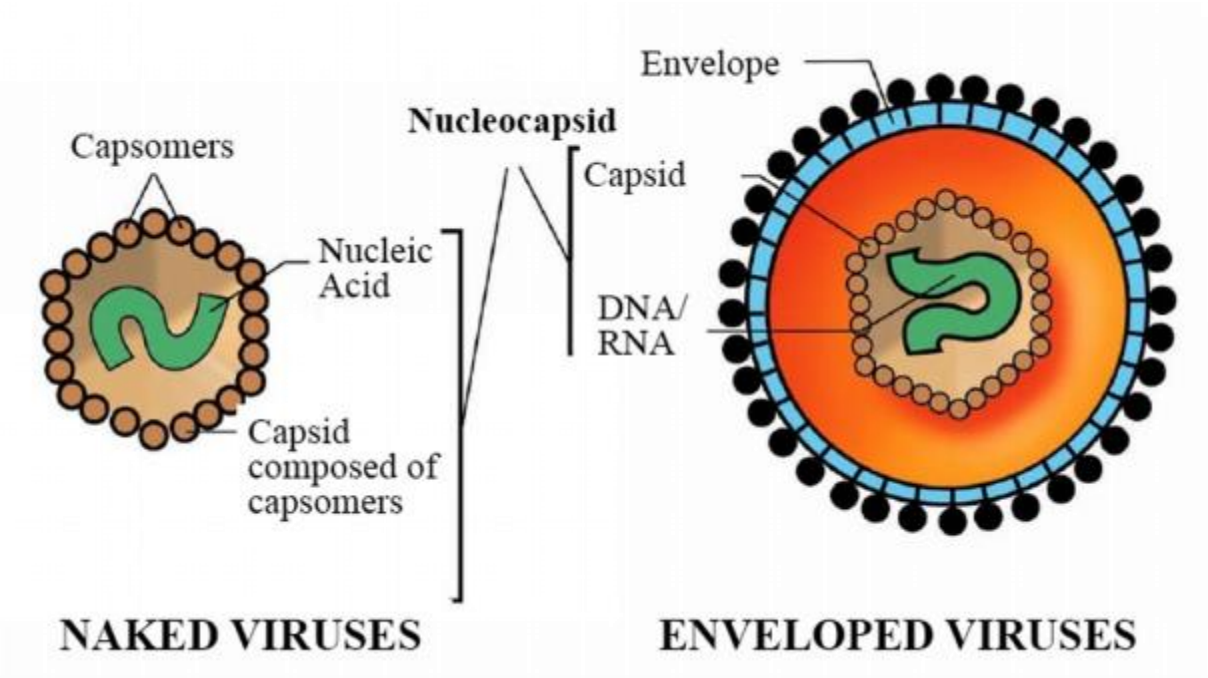

Figure 06: Enveloped virus and naked virus

The comparison between eukaryotic, prokaryotic and virus highlights the structural and functional diversity of living organisms at the cellular level.

Eukaryotic cells, characteristic of multicellular organisms and certain unicellular organisms, are distinguished by their complex internal organisation, including a membrane-bound nucleus and numerous compartmentalised organelles. Prokaryotic cells, which are simpler and older, lack a nucleus and membrane-bound organelles, but are remarkably efficient in their functioning, particularly due to their great adaptability. Finally, virus, represented mainly by viruses, has no cellular structure of their own and is incapable of reproducing on their own, which places them on the margins of life, at the boundary between inert matter and biological life.

Thus, the comparative study of these three types of organization highlights the evolution of biological systems, from rudimentary forms to the most complex cellular structures, and underlines the importance of the concept of the cell as the basic unit of life – while showing that there are notable exceptions to this principle.

2. Methods of studying cells

The study of cell structure, chemical composition and functioning (physiology) has required the development of appropriate, sophisticated tools and techniques. Various methods have been developed to study different aspects of cells: morphological, chemical, biochemical and physiological.

2.1. Optical and electron microscopy methods

Microscopy by definition is the set of techniques used to obtain an image of biological structures. It is divided into two main groups:

- ✓ **optical**, also called **photonic**, because it uses photons
- ✓ **electron**, which uses electrons to study the object

Advances in microscopy have made it possible to push back the boundary between the visible and the invisible.

2.1.1. Optical or light microscopy

Optical microscopy is an old technique, of which there are many variants. The principle of this technique is that a specimen is illuminated by a lamp, and the molecules to be observed interact with the light in several ways:

- ✓ Either by **absorbing** certain wavelengths of light. This is ***direct light microscopy***.
- ✓ Or by **causing a phase shift** in the different light rays. This is phase ***contrast microscopy***.
- ✓ Or by **emitting light** at a different wavelength than the original one. This is ***fluorescence microscopy***.

An **optical microscope** is an optical instrument equipped with an objective lens and an eyepiece that magnifies the image of a small object (its magnification) and separates the details of that image (its resolution) so that it can be observed by the human eye. This instrument offers the following advantages:

- ✓ ***provides a general view of cells or tissues***
- ✓ ***allows the examination of living cells***.

However, it has the following limitations:

- ✓ The resolving power of an optical microscope cannot exceed 0.2 µm,
- ✓ With a maximum magnification of 1000×.

2.1.1.1. Introduction to the optical microscope

An optical microscope generally consists of (figure 07):

- ✓ ***A stand*** (base) that ensures the stability of the device,

- ✓ ***An optical tube*** along which there is a system of glass lenses and at each end of which there is an eyepiece for collecting the image and an objective lens for magnifying the image of the specimen a certain number of times,
- ✓ ***A stage*** (object holder) with a hole in it and equipped with clamps to hold the slide in place
- ✓ ***Light source*** illuminating the specimen.

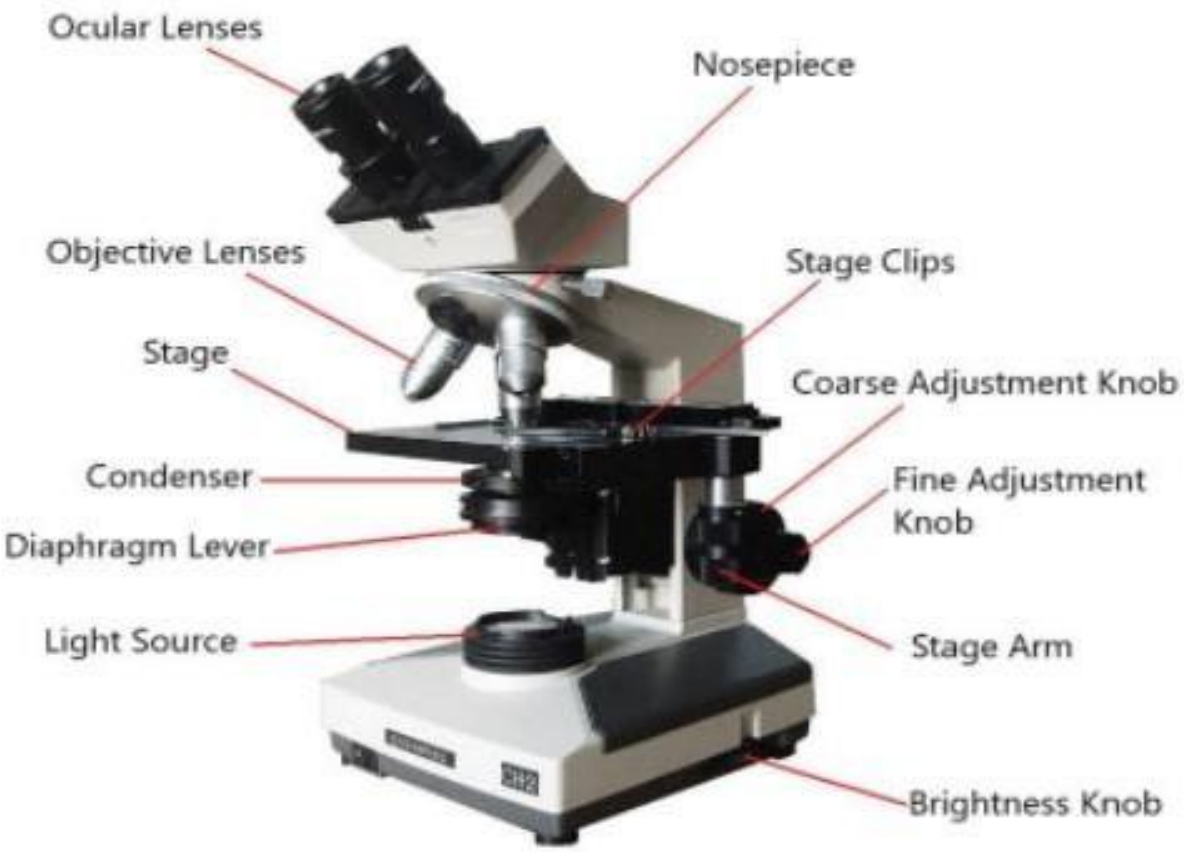

Figure 07: Optical microscope

The microscope is characterised by:

- ✓ Its **magnification or power**: equal to the product of the magnification (or power) of the objective lens and the eyepiece. The greater the magnification of the objective lens, the closer the objective lens must be to the object being observed.
- ✓ Its **resolving power**: The resolution of a microscope refers to its ability to separate very close details. It is fundamentally limited by the diffraction of light.

2.1.1.2. Principle of Microscope Operation

Two types of observation are possible in microscopy:

- ✓ ***Transmission*** observation for optical microscopes and transmission electron microscopes. The sample is penetrated by photons and electrons; glass lenses (OM) or electromagnetic fields (TEM) produce an image that is captured by the eyepiece (OM) or fluorescent screen (TEM).
- ✓ ***Reflection*** observation for scanning electron microscopes. The microscope only captures the rays reflected by the walls of the preparation. This type of microscopy provides an image of the surface of objects rather than their internal structure. This type of microscope is rarely used; it corresponds to the dark field microscope in optical microscopy and the scanning electron microscope.

2.1.1.3. Conditions for observation under a microscope

For better observation under a microscope, **two conditions are necessary**:

- ✓ ***Sample thickness***: better observation requires a thin sample preparation. This allows the incident beam of photons or electrons to pass through, so it is necessary to make very thin sections.
- ✓ ***Contrast***: Transmission observation is only possible if certain areas of the section absorb photons or electrons more than others (contrast effect). Cellular components have very little contrast between them. For better observation, a staining step is necessary to increase contrast.

2.1.1.4. Examples of optical microscopes

- **Dark field microscope**

The dark field microscope (Figure 08) reveals certain details when observing living cells by increasing natural contrasts. In this type of microscope, the light source is oblique to the cell preparation. A special condenser illuminates the specimen: only the reflected rays are captured by the objective lens. The background of the field of view is black, and even the ***smallest object appears brightly lit***.

The dark field microscope is mainly used to observe live and low-contrast microorganisms, for unstained living specimens and surface details.

Figure 08: Trinocular dark field microscope

Phase contrast microscope

This type of microscope (Figure 09) is widely used for observing living cells. It is a good tool for observing the movements of cells and their organelles, such as mitochondria and chromosomes, and for monitoring cellular processes, such as mitosis. The images observed can be recorded by a video camera.

Figure 09: Contrast microscope

Fluorescence microscope

This type of microscope (Figure 10) allows the fluorescence emitted by fluorescent markers introduced into the sample being studied to be visualised. **Fluorescent molecules** (fluorescein) **absorb radiation** at a given wavelength and **emit radiation at a higher wavelength.**

This instrument is **similar to an ordinary light microscope**, except that it is equipped with a **UV light source (UV lamp**) and **a filter system** (necessary to select the appropriate UV wavelength for each fluorescent marker).

The fluorescence microscope allows you to:

• Visualise objects that are naturally fluorescent (chlorophyll, vitamin A, etc.), or molecules that have been made fluorescent in order to observe them more clearly and, if necessary, track their movement.

• Study biological structures, their functioning and their interactions (cell division, motility, transport, secretion, neuronal communication, etc.) at the cellular and molecular level.

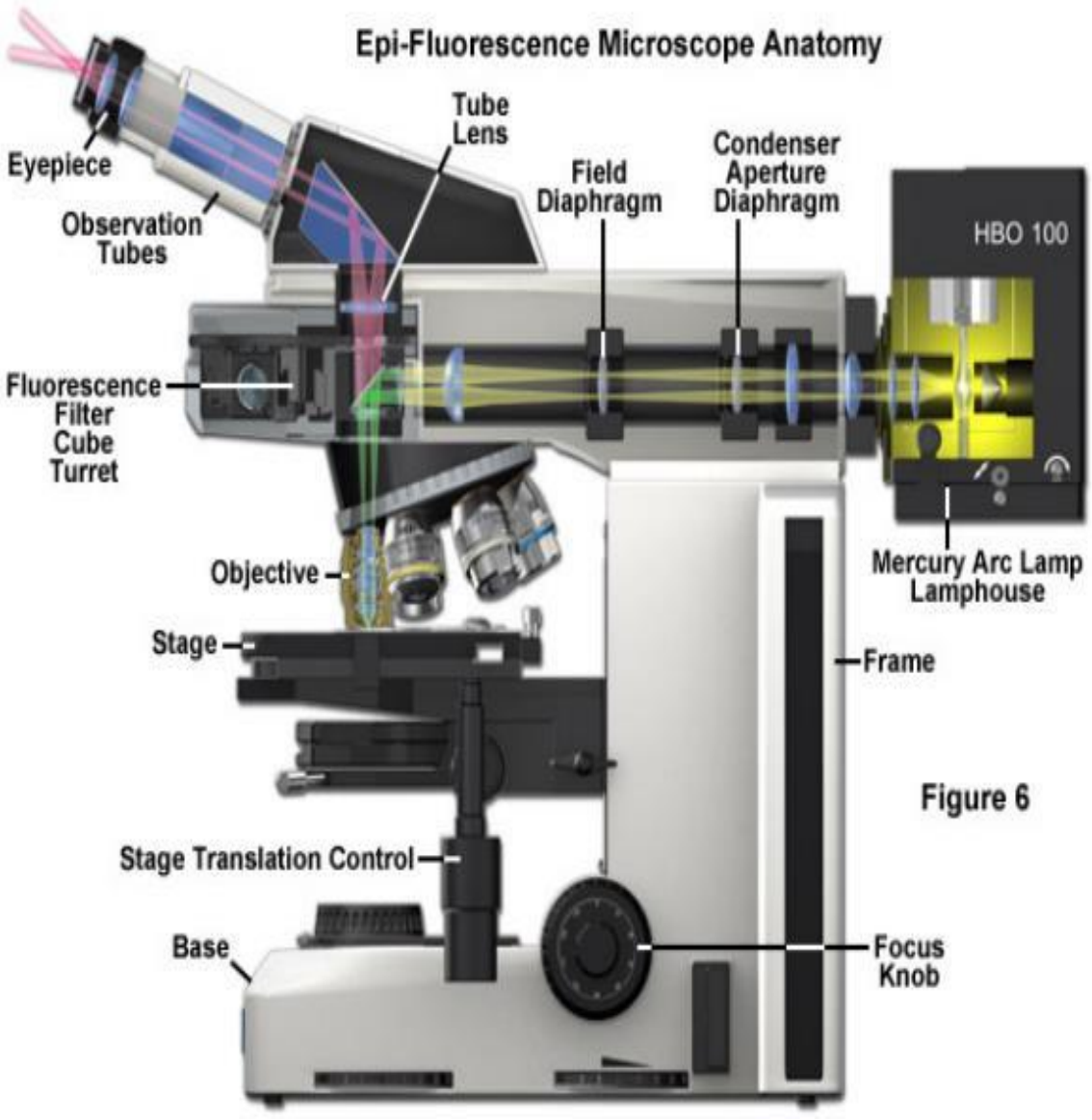

Figure 10: Epi Fluorescence Microscope

2.1.2. Electron microscopy

Electron microscopy is a much more recent technique. The first microscope was built in 1931 by Max Knoll and Ernst Ruska (Nobel Prize in Physics in 1986).

An electron microscope is an observation device that uses a beam of electrons instead of light to view very small structures that are invisible with an optical microscope. It allows for much higher magnification and resolution.

In this type of microscope (Figure 11), electromagnetic lenses and a beam of electron particles are used to view infinitely small objects: it is even possible to access the ultrastructure of organelles.

There are two types of electron microscope:

• Transmission electron microscope (TEM)

- • Scanning electron microscope (SEM).

Sample preparation:

• Samples must be dehydrated, fixed (often with agents such as glutaraldehyde) and placed under vacuum, as electrons cannot travel through air.

• Samples are often coated with a thin layer of conductive metal (such as gold or platinum) to facilitate observation.

- **Advantages**:

• Very high magnification (up to 1,000,000×).

• High resolution (up to a few nanometres).

• Allows organelles, viruses and even macromolecules to be seen.

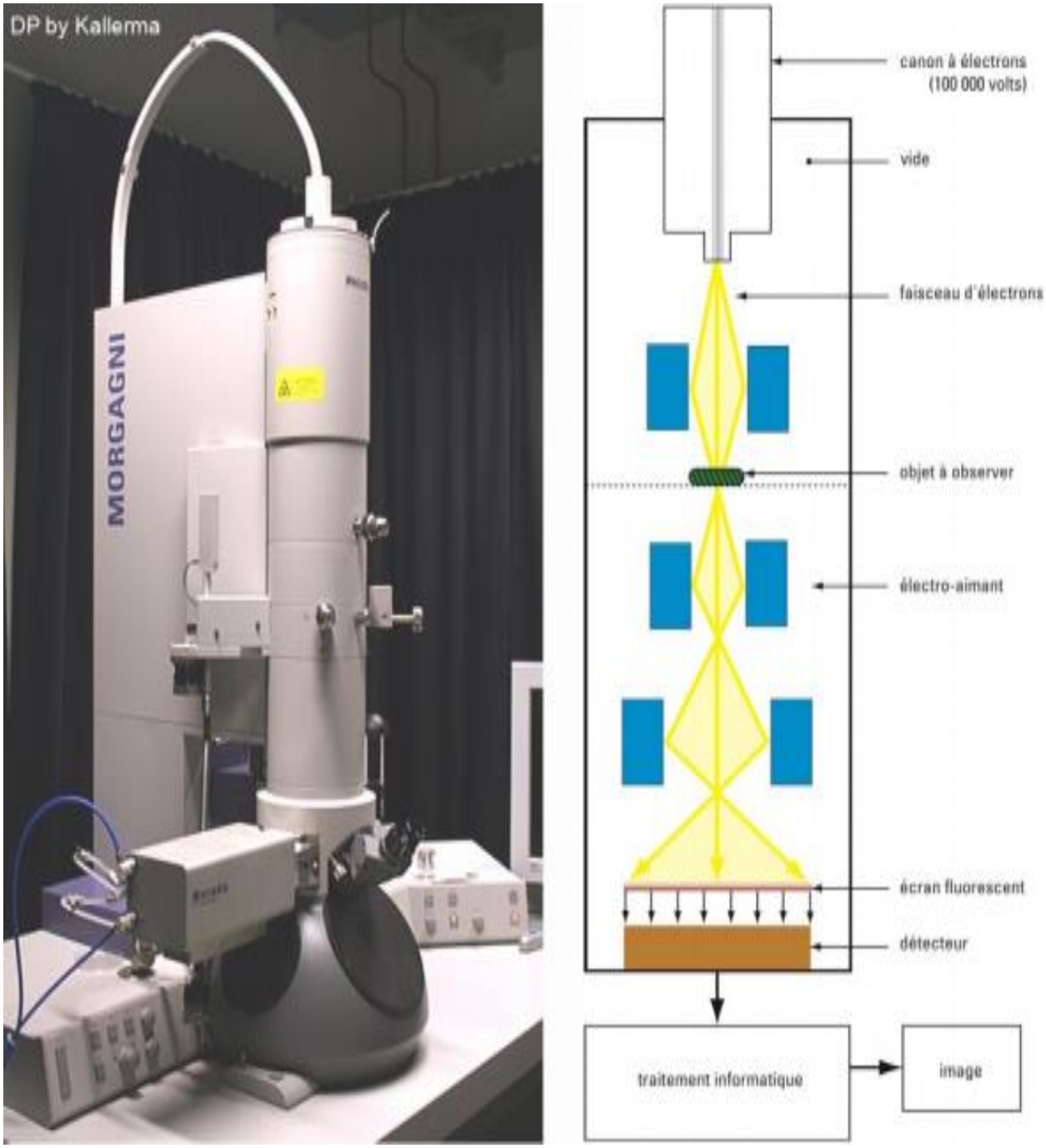

Figure 11: Principle of operation of an electron microscope

- **Disadvantages:**

• High cost and complex maintenance.

• Requires lengthy and often destructive sample preparation.

• Observation is only possible on dead samples, as the vacuum and treatments do not allow living organisms to be observed.

- **Applications:**

• Study of cellular ultrastructure (membranes, mitochondria, ribosomes, etc.).

• Visualisation of bacteria, viruses and subcellular structures.

• Medical research, virology, nanotechnology, materials science, etc.

The main differences between optical microscopy and electron microscopy are as follows (table 02):

- ✓ Optical microscopes use a beam of light, whereas electron microscopes use a beam of electrons.
- ✓ Optical microscopes use glass lenses, whereas electron microscopes use electrostatic and magnetic lenses.
- ✓ With optical microscopes, it is possible to magnify up to 1000-1500 times the actual size, while the magnification is much higher (up to 1,000,000 times) with an electron microscope.
- ✓ Resolution is limited in optical microscopy, while it is good in electron microscopy.

Table 02: Comparison between optical microscopes and electron microscopes.

Criteria	**Optical microscope**	**Electron microscope**
Light source	Visible light	Electron beam
Observation medium	Air	**Vacuum**
Resolution	~200 nm	~0,1 à 0,5 nm
Image type	Colour, real and direct image	Black and white, indirect image (via screen or sensor)
Sample preparation	quick, non-destructive	Complex, time-consuming, often destructive
Applications	Teaching, histology, basic cell biology	Advanced research, virology, cell ultrastructure

The optical microscope uses light to observe cells and tissues at moderate magnifications (up to approximately 1500×) and allows living cells to be studied with a simple preparation. In contrast, the electron microscope uses an electron beam, which allows for much higher magnifications and resolution, making subcellular structures such as mitochondria, ribosomes, or viruses visible. However, it requires complex preparation, a vacuum environment, and can only

be used on dead samples. Thus, each type of microscope has its specific advantages, depending on the type of observation desired.

2.2. Histochemical methods

Histochemical methods are techniques used to locate and identify specific chemical components (proteins, carbohydrates, lipids, nucleic acids, enzymes, etc.) in cells and tissues, using chemical reactions that are visible under a microscope (often through staining).

Histochemical techniques enable the specific identification of intracellular structures such as mitochondria, the nucleus, the Golgi apparatus and certain enzymes, based on their chemical composition.

- **Objectives of histochemical methods:**

• Identify the chemical nature of cellular structures.

• Detect the presence or activity of certain molecules or enzymes.

• Study the intracellular or tissue location of components.

2.2.1. Main histochemical methods

- **Classic staining (routine histochemistry)**

➢ ***Haematoxylin-eosin (H&E) staining***:

• Haematoxylin: stains nuclei blue-purple.

• Eosin: stains cytoplasm and proteins pink.

• Used for general tissue observation.

- ***PAS (Periodic Acid-Schiff) staining***:

• Highlights carbohydrates (glycogen, mucins, cell walls, etc.).

• Structures rich in polysaccharides turn pink/purple.

- **Toluidine blue staining:**

• Stains nucleic acids and basophilic granules.

• Also used in electron microscopy (pre-treatment).

- **Enzymatic histochemistry**

• Allows enzymatic activity to be located directly within the cell.

• Examples:

- ✓ Acid/alkaline phosphatases: lysosomal activities.
- ✓ Peroxydases: activity in certain immune cells.

• Requires specific substrates that become coloured during the enzymatic reaction.

- **Methods for detecting lipids**

• Use of lipophilic dyes such as: Oil Red O, Sudan III/IV: stain lipid droplets.

• These dyes are soluble in lipids → specific localisation.

- **Methods for detecting nucleic acids**

• Feulgen staining: specific for DNA (after acid hydrolysis).

• Methyl green-pyronin staining: differentiates between DNA (green) and RNA (red).

- **More advanced methods (complementary to histochemistry)**

• Immunohistochemistry: uses antibodies to locate specific proteins.

• In situ hybridisation: to detect specific DNA or RNA sequences.

These techniques are not always considered ‘classical’ histochemistry, but are commonly used as a complement.

Histochemical methods are essential in cell biology for studying the biochemical composition of cells. Through specific chemical reactions, they enable the localisation of key molecules in tissues and cells, thereby facilitating understanding of their function, organisation and pathology.

The various techniques used are:

1) Cell organelle isolation technique (fractionation of constituents by centrifugation).

2) Autoradiography (radioactive isotopes).

3) Enzymatic technique.

4) Cytoimmunological technique.

- **Technique for isolating cell organelles (centrifugation and ultracentrifugation)**

In order to isolate intracellular organelles, cell fractionation is necessary. This fractionation consists of breaking down the cell membranes (by grinding, for example) in the presence of an isotonic liquid in order to best preserve the intracellular organelles.

The homogenate obtained after cell fractionation is subjected to successive centrifugations in order to separate the various fractions. The supernatant is centrifuged several times (ultracentrifugation), increasing the speed each time.

This process first separates the large cell debris, then the nuclei, followed by the plastids, mitochondria and finally the lightest particles (the ‘supernatant’ containing soluble substances).

Fractionation allows large quantities of cell components to be isolated for the purpose of studying their composition and metabolism.

- **Autoradiography (radioactive isotopes).**

This technique is used to determine activity within the cell cytoplasm using a molecule that is specifically involved in this cellular activity. It involves labelling a cellular substance with a radioactive element and then locating it using radioactivity detectors (Geiger-Müller counter) or simple photographs.

By examining the photos under a microscope, it is possible to determine the location of the labelled molecules, and by making several microscopic observations, it is even possible to deduce the path taken by these labelled molecules (the substance being studied).

Example: by labelling thymine, it is possible to highlight the location of DNA (thymine nucleotide present specifically in DNA) or the site of DNA replication.

- **Enzymatic technique**

These techniques are based on the detection of products from added enzymes that have been provided with their specific substrate.

Example: various phosphatases hydrolyse organic phosphates (nucleotides), resulting in the formation of a granular precipitate that can be observed under an optical or electron microscope.

- **Cytoimmunological technique**

These are immunological techniques based on the use of antigens and antibodies, followed by detection using various methods such as those involving direct labelling of antibodies (Ab) or antigens (Ag), or immunoenzymatic methods (ELISA = Enzyme-Linked ImmunoSorbent Assay and immunoblot), etc. .

Cytoimmunological techniques enable the intracellular localisation of typical organelles and macromolecules. The aim of immunochemistry is to reveal a biological molecule present on a cell or tissue using specific antibodies.

Example: the antibody is labelled with 'Peroxidase', which can be detected by electron microscopy using triaminobenzedine in the form of an opaque precipitate.

3. Plasma membrane: structure and function

The **plasma membrane**, also known as the ***cytoplasmic membrane*** or ***plasmalemma***, is a protective envelope made up of a layer of molecules that separates the cell from its environment and delimits the organelles within it.

It is a dynamic structure that separates the intracellular environment (hyaloplasm or cytosol) from the extracellular environment, controls exchanges between the cell and its environment, and is selectively permeable: it allows certain substances to pass through more easily than others.

3.1. Membrane components

The structure of the plasma membrane is undetectable under an optical microscope; it can only be observed under an electron microscope. It appears to be formed of three layers, two dense sheets separated by a clear sheet.

The composition of cell membranes, determined by separating the different components of cells and conducting chemical analyses, has revealed three main components: lipids, proteins and carbohydrates.

3.1.1. Lipids

The lipids that make up the plasma membrane are mainly phospholipids, cholesterol (animal cell membrane, plant cell replaced by other types of sterols: sitosterol and stigmasterol) and glycolipids (carbohydrate chains linked to phospholipids on their extracellular side).

Thus, the main types of membrane lipids

• **Phospholipids**: the most abundant (e.g., phosphatidylcholine, phosphatidylethanolamine)

• **Cholesterol**: modulates membrane fluidity and stability

• **Glycolipids**: involved in cell recognition and cell surface protection

The lipids that make up the membrane have the following properties:

• **Self-assembly**: lipids organise themselves or assemble into a bilayer thanks to their amphiphilic or bipolar nature (hydrophilic head and hydrophobic tail).

• **Fluidity**: the plasma membrane is fluid due to the movements of lipids, which can be classified as: **frequent and rapid movements** (lateral diffusion and rotation), **rare and very slow movements** (tilting or flip-flop). **The fluidity** of the membrane **increases proportionally** with the **percentage of unsaturated fatty acids** and **decreases with that of cholesterol.**

- **Mechanical stability**: the membrane is more stable when it is rich in cholesterol.
- **Asymmetry**: the lipid composition varies between the two hemimembranes.

3.1.1.1. The functions of membrane lipids

Membrane lipids are essential components of the plasma membrane and internal cell membranes. Their role is not limited to structure: they perform several crucial functions, including:

- **Structural role**

• ***Formation of the lipid bilayer***: Lipids (mainly phospholipids) form a lipid bilayer that constitutes the backbone of the membrane. This structure is fluid, flexible and semi-permeable, allowing the membrane to adapt and remodel itself.

• ***Maintaining cellular integrity***: They separate the interior of the cell from its external environment, creating a closed and protected compartment.

- **Selective barrier**

The lipid bilayer is **permeable to small hydrophobic molecules** but **impermeable to ions and polar molecules**, allowing **precise control of exchanges between the interior and exterior of the cell.**

- **Platform for membrane proteins**

Lipids create a favorable environment for the anchoring and functioning of membrane proteins, which perform various roles (transport, receptors, enzymes, etc.).

- **Energy Reserve (Secondary)**

Some membrane lipids can serve as energy reserves, although this is not their primary function. They can be broken down to provide fatty acids when energy is needed.

- **Role in Cell Recognition**

Certain lipids (particularly glycolipids) present on the membrane surface play a role in cell-cell interactions, recognition by the immune system, and cell adhesion.

3.1.2. Proteins

The proteins that make up the membrane are classified into two categories (depending on their nature):

- ✓ **holoproteins** (**pure proteins**)
- ✓ **heteroproteins** (**glycoproteins** consisting of a protein and a carbohydrate moiety with linear or branched chains).

Membrane proteins exhibit two modes of organization:

- ***Intrinsic organization*** "***Integrated proteins***": When they cross the lipid bilayer, they are called transmembrane (hydrophobic), and they are either:

- ✓ integrated into the outer dense layer and bound by a covalent bond (stable) to a phosphatidyl-inositol (GPI) group
- ✓ integrated into the inner dense layer by covalent bonds to one or more fatty acids

- ***Extrinsic organization*** "***Peripheral proteins***": These are called hydrophilic proteins, either external (exoplasmic) or internal (protoplasmic), and are often bound to transmembrane proteins by non-covalent bonds (unstable).

Membrane proteins are distinguished by the following properties:

- ***Fluidity***: Due to the large size of protein molecules, they are characterized by less frequent, slow movements, mainly represented by lateral diffusion within the lipid bilayer.

- ***Asymmetry***: Membrane proteins exhibit a different distribution on the two surfaces.

3.1.2.1. The Functions of Membrane Proteins

Membrane proteins are essential components of the plasma membrane (and internal membranes). They are responsible for many functions essential to the proper functioning of the cell.

Their main functions are:

- ➢ **Membrane Transport**

• Certain proteins allow the selective passage of molecules across the membrane.

• We distinguish:

- ✓ **Channels**: allow certain ions or molecules to pass through a gradient (e.g., potassium channel).
- ✓ **Transporters** (or permeases): change conformation to transport substances.
- ✓ **Pumps**: consume energy (ATP) to actively transport molecules (e.g., Na^+/K^+ pump).

- ➢ **Reception and transmission of signals (receptors)**

• Some proteins act as receptors: they recognize signaling molecules (e.g., hormones, neurotransmitters) on the cell surface.

• This triggers an intracellular signaling cascade, which modifies the cell's activity. Example: hormone receptors (adrenaline, insulin).

- **Cell Adhesion**

• Certain proteins allow cells to attach to other cells or to the extracellular matrix.

• This is essential for tissue formation and cell-to-cell communication.

* Examples: integrins, cadherins, selectins.

- **Enzymatic Activity**

• Some membrane proteins are enzymes.

• They catalyze specific reactions directly on the membrane surface.

 Example: Na^+/K^+ ATPase, an enzyme that pumps ions.

- **Cell Recognition**

• Membrane proteins can carry carbohydrate groups (glycoproteins) that serve to identify cells.

• This is important for immune responses, transplant compatibility, etc.

 Example: red blood cell surface antigens (ABO blood groups).

- **Membrane Organization and Structuring**

• Certain proteins play a role in anchoring the cytoskeleton to the membrane or in organizing membrane microdomains (such as lipid rafts).

• They contribute to cell shape, mobility, and cell division.

3.1.3. Carbohydrates

Membrane carbohydrates (or membrane sugars) are carbohydrate chains attached to lipids or proteins present in the plasma membrane. They are never free:

• When they are attached to a protein, they are called glycoproteins.

• When they are attached to a lipid, they are called glycolipids.

3.1.3.1. Functions of Membrane Carbohydrates

- **Cell Recognition**

• Carbohydrates play a key role in cell identity.

• They allow cells to recognize each other, which is essential for tissue formation and intercellular communication.

Example: ABO blood group antigens are specific carbohydrates found on red blood cells.

- **Cell Surface Protection**

• The glycocalyx protects the cell against:

- Mechanical or chemical attacks
- Digestive enzymes
- Pathogens

It can also retain water around the cell, which promotes hydration and lubrication of tissues (e.g., intestinal cells).

- **Cell Adhesion**

• Carbohydrates contribute to adhesion between cells or between a cell and the extracellular matrix.

• This facilitates tissue formation and the maintenance of its structure.

 Example: During inflammation, immune cells use receptors to recognize carbohydrates on the surface of endothelial cells and bind to them.

- **Participation in cell signaling**

• Certain carbohydrates can interact with specific receptors, playing a role in signaling between cells (particularly in the immune system).

• They can also modulate the activity of membrane proteins

The plasma membrane (Figure 12) is an asymmetric fluid mosaic according to the model proposed by Singer and Nicolson (1972).

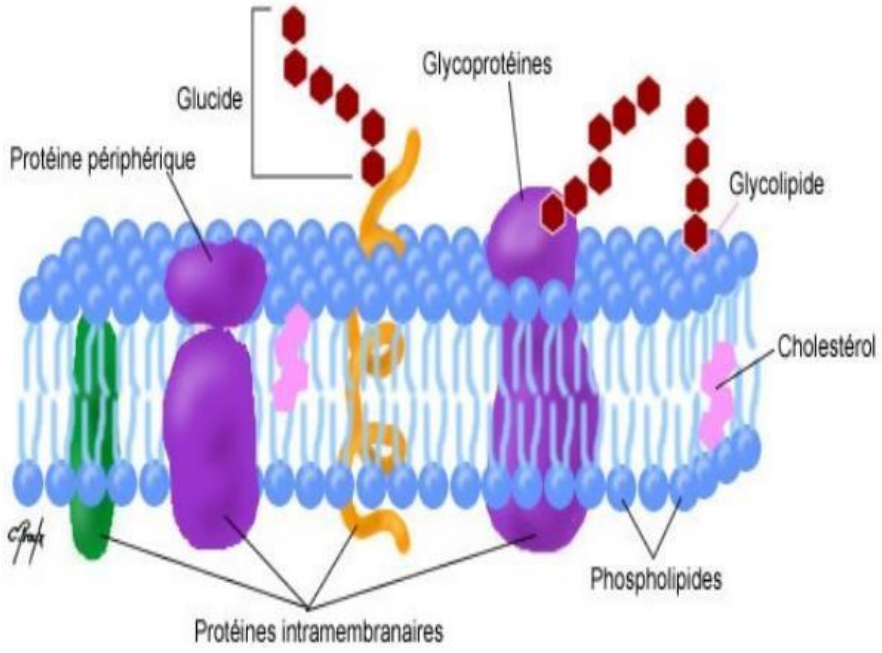

Figure 12: Molecular architecture of the plasma membrane.

3.2. Physiological roles

The membrane fulfills several essential and important physiological roles for this cell.

3.2.1. Control of exchanges between the extracellular environment and the intracellular environment

- ***Exchanges without deformation of the plasma membrane***

This type of exchange ensures the transport of small molecules, without the intervention of the cytoskeleton. Two types of transport should be described: ***passive transport*** and ***active transport.***

- ***Passive transport:*** during passive transport, the molecules are transported in the direction of their concentration gradient, without consuming ATP. Passive transport can be ***simple*** or ***facilitated.***
- ***Simple diffusion***: a transport without permeases, through the lipid bilayer. As an example: hydrophobic and uncharged molecules such as H2O, CO2, O2, N2, benzene, ethanol....

The main factors regulating simple diffusion are:

• Size ***of molecules***: these are specific diffusions for small-sized molecules.

• ***Absence of polarity***: a polarized molecule does not cross the membrane by facilitated diffusion.

• ***Absence of charge***: a charged molecule, even of very small size, does not penetrate the lipid bilayer.

• ***The partition coefficient***: it is the ratio of solubility in lipids/solubility in water; the higher this ratio, the easier the substance's transmembrane passage increases

- ***Facilitated diffusion***: this type of diffusion is done through protein channels (Na+, K+, Cl-), either by specific carrier proteins or permeases for the transport of glucose, amino acids...).

Active Transport

Two types of transport assets are to be described : ***primary transport*** and ***secondary transport***

- ***Primary Transport:***

This type of Transport also called direct active transport. This transport requires energy obtained by the hydrolysis of ATP, is done against the gradient concentration and involves enzymes called transmembrane ATPases or pumps.

- ***Secondary transport***:

The energy required for this transport is not provided by the hydrolysis of ATP, it is the difference in electrochemical potential that is used. The two main forms of secondary transport are:

- ***The symport***: during this transport two substances of different nature are transported in the same direction (co-transport), one is in the direction of its concentration gradient (passive transport) and the other in the opposite direction to its concentration gradient (active transport).

- ***Antiport***: this type of exchange ensures the transport of two or more substances of different nature in opposite directions (counter-transport). One is transported in the direction of the concentration gradient and the other against the concentration gradient.

Figure 13 summarizes the different types of membrane transport. Figure 14 summarizes the two main types of active transport.

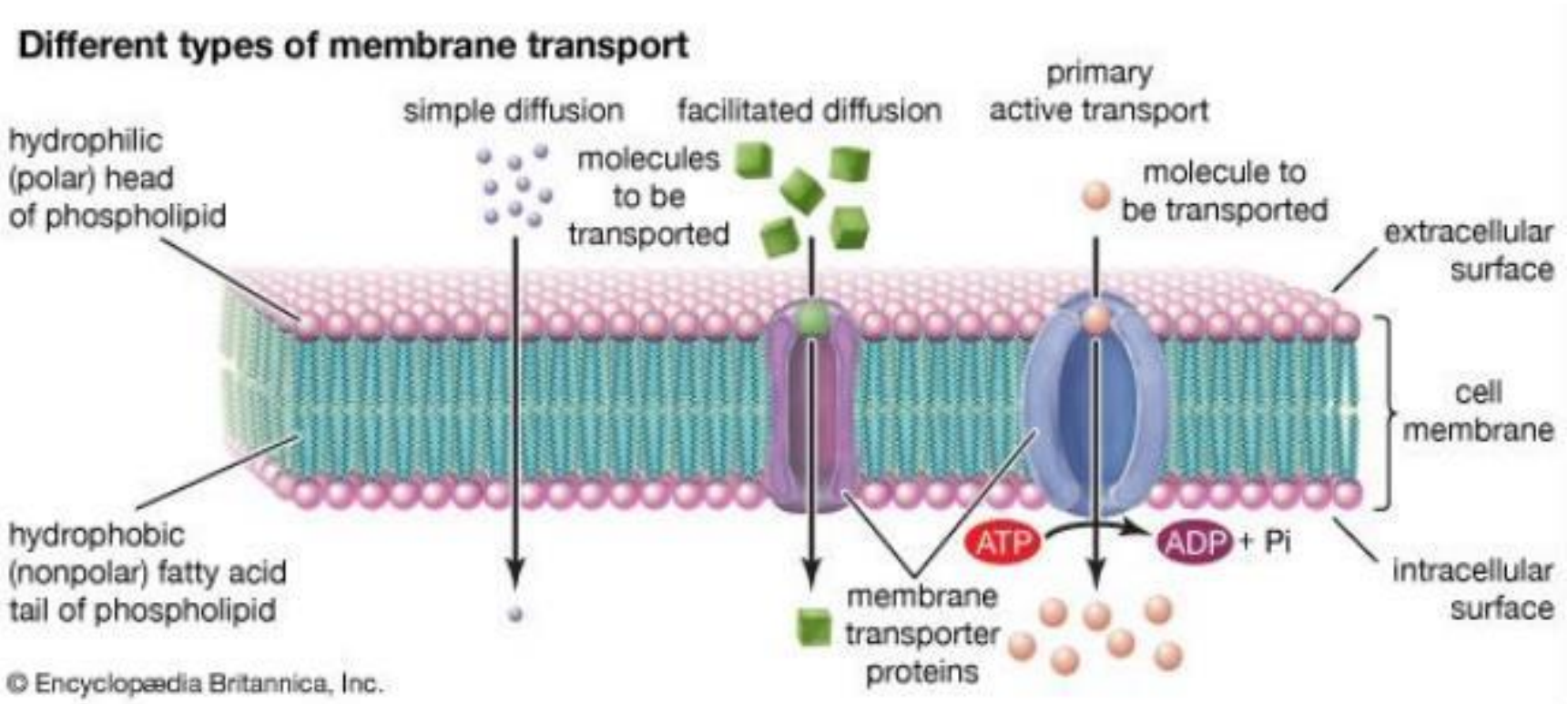

Figure 13: the different types of membrane transport

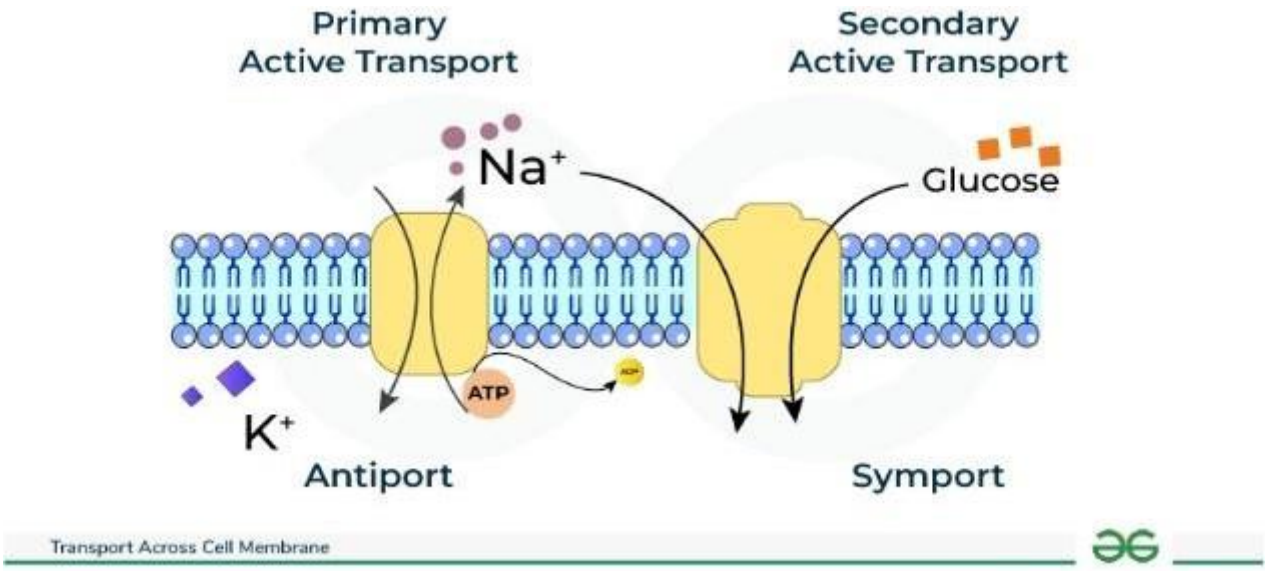

Figure 14: The two main types of active transport.

- ***Exchanges with deformations of the plasma membrane***

This type of exchange ensures the transport of large molecules or particles with intervention of the cytoskeleton. two forms of exchange are possible: case of endocytosis and exocytosis.

- ***Endocytosis***:

This type of transport allows the molecules to enter the cell. Three types of endocytosis are known: pinocytosis, phagocytosis, and receptor-mediated endocytosis (Figure 15).

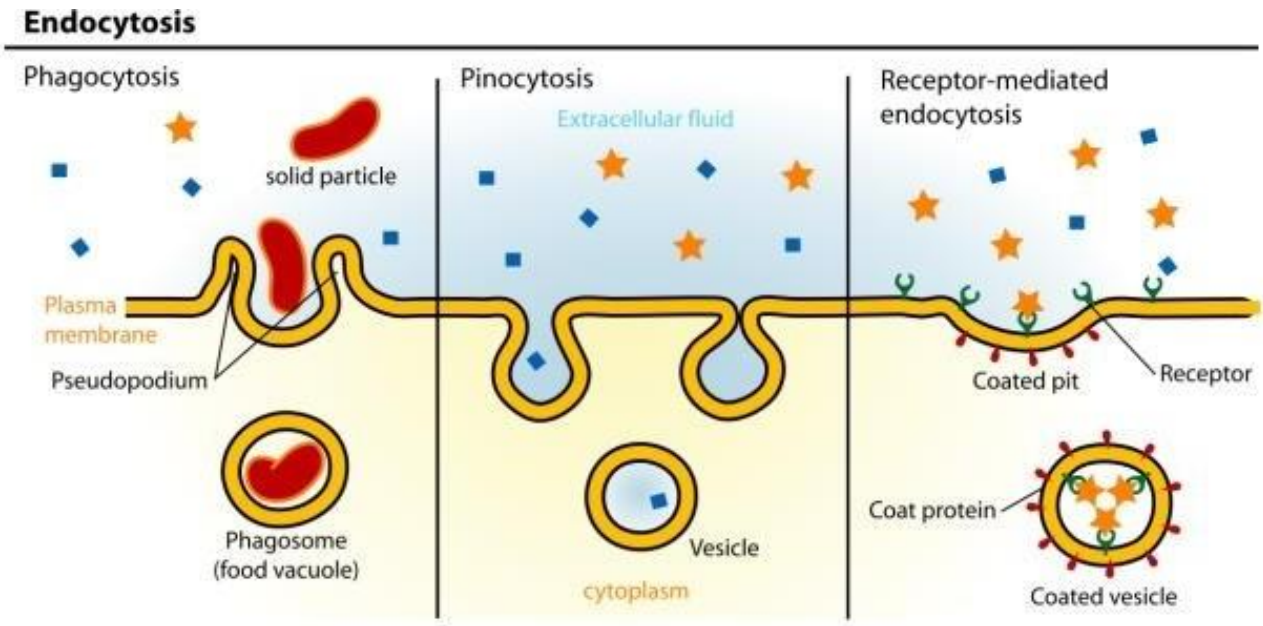

Figure 15. The three types of endocytosis

Endocytosis is a cellular process through which the cell takes in substances from its environment by enclosing them in membrane-bound vesicles. There are three main types of endocytosis: **phagocytosis**, **pinocytosis**, and **receptor-mediated endocytosis**.

Phagocytosis is used mainly by certain cells like macrophages to engulf large particles such as bacteria or cellular debris.

Pinocytosis, often called "cell drinking," allows the cell to take in extracellular fluid and the small molecules it contains, without any specific targeting.

In contrast, **receptor-mediated endocytosis** is a highly specific process in which targeted molecules (such as hormones or nutrients) bind to receptors on the cell membrane, triggering the formation of vesicles that bring them into the cell. These mechanisms are essential for cell nutrition, communication, and defense.

❖ *Exocytosis*

Exocytosis ensures the exit of secretion molecules to the extracellular environment. It allows the recycling of membrane receptors. Process that allows the transport of particles from the intracellular to the extracellular medium

Exocytosis is a cellular process by which a cell expels substances to the outside environment. This mechanism involves the fusion of intracellular vesicles with the plasma membrane (figure 16), allowing the contents of the vesicles to be released outside the cell.

Exocytosis is essential for various cellular functions, such as the secretion of hormones, neurotransmitters, enzymes, or the removal of waste products. It also plays an important role in renewing and maintaining the plasma membrane. This process can be **constitutive**, meaning it happens continuously, or **regulated**, meaning it requires a specific signal (such as a nerve impulse or a hormonal stimulus) to be triggered.

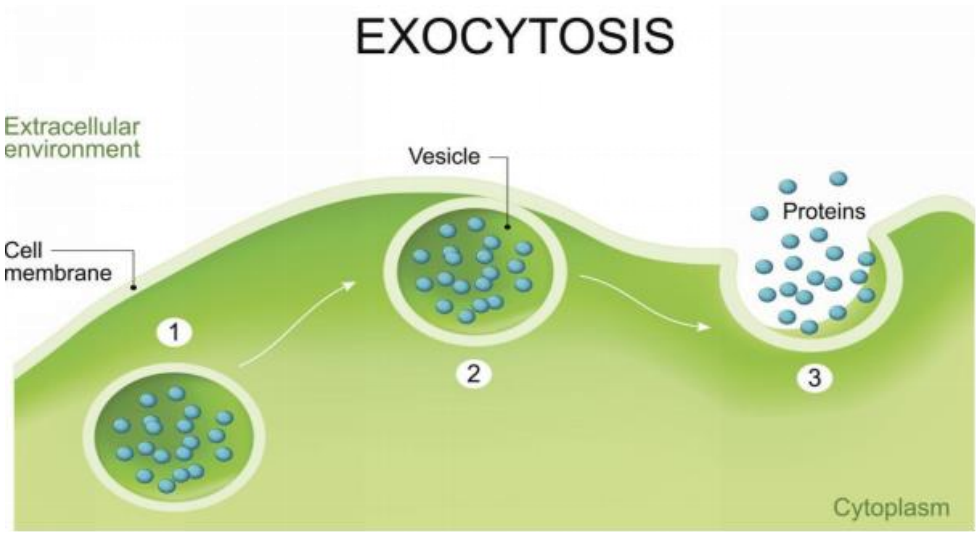

Figure 16: Exocytosis

3.2.2. Transmission of information: Hormonal information

The **plasma membrane** plays a key role in the **transmission of hormonal signals**, but its involvement depends on the nature of the hormone. **Water-soluble hormones**, such as insulin or adrenaline, **cannot cross the lipid bilayer** of the membrane. Instead, they bind to **specific receptors on the cell surface**, which then activate internal signaling pathways—a process known as **signal transduction**—leading to a cellular response without the hormone entering the cell. In contrast, **lipid-soluble hormones**, such as steroid hormones (e.g., cortisol, estrogen), **can diffuse directly through the plasma membrane** due to their lipophilic nature. Once inside, they bind to **intracellular receptors** in the cytoplasm or nucleus, and the hormone-receptor complex directly influences **gene expression** by interacting with DNA. Thus, the plasma membrane acts as a **signal gateway for hydrophilic hormones** and as a **selective barrier** for lipophilic hormones that act within the cell.

4. Cytoskeleton and cell motility

The cytoskeleton is specific to eukaryotic cells. The cytoskeleton is located at: Cell periphery, in the cytoplasm and the nucleoplasm.

The cytoskeleton is a complex network of protein filaments (figure17) extending throughout the cytoplasm, and organizing it, allowing eukaryotic cells to adapt to a wide variety of morphological changes, to perform coordinated movements.

This organelle is responsible for the ability of eukaryotic cells to organize the content of their cytoplasm, change shape and move. The presence of a cytoskeleton allows the cell to maintain its shape and resist collapse.

The cytoskeleton is a very dynamic structure, neither rigid nor articulated, which continuously reorganizes itself during different cellular events (migration, division, etc.). The cytoskeleton is a dynamic system that constantly assembles and disassembles and requires Energy (GTP and ATP)

This cytoskeleton appears in the cytosol as impressive scaffolding formed by fibrillar proteins called "fibrils". The cytoskeleton consists of three types of protein filaments: microtubules, microfilaments, and intermediate filaments.

- ***Microtubules*** are unstable and polarized polymers present in the hyaloplasm, they are highlighted by the technique of immunofluorescence. ***Microtubules*** are made up of two types of globular proteins, alpha (α) and beta (β) tubulins, which combine to form dimers. In the presence of GTP and Mg++, the dimers polymerize into protofilaments. The association of 13 protofilaments gives a microtubule (hollow tube) of 25nm in diameter. So microtubules are very thin hollow tubes made of a protein called ***tubulin***.

Microtubules perform several functions such as:

- ✓ maintaining the cell's shape,
- ✓ movement of chromosomes in mitosis and meiosis
- ✓ transport of endocytosis and exocytosis vesicles
- ✓ movement of intracellular organelles,.....

- ***Microfilaments***, present under the cell membrane, are protein filaments of 5-6 nanometers in diameter, made up of a protein called ***actin c***ontained in large quantities in the muscles. Each filament of actin is formed by two strands of subunits arranged in a string, twisted together like a rope. These globular subunits are stabilized by calcium ions and associated with ATP molecules that provide the energy needed for the contractile mechanism.

- ***Intermediate filaments*** have an intermediate size between microfilaments and microtubules (10-15 nm in diameter). Their role is purely structural and fundamental, they do not intervene in cell motility.

These protein filaments assemble together to form larger filaments and connect the intracellular structures to each other and to the proteins of the plasma membrane, constituting a resistant framework of cells and tissues.

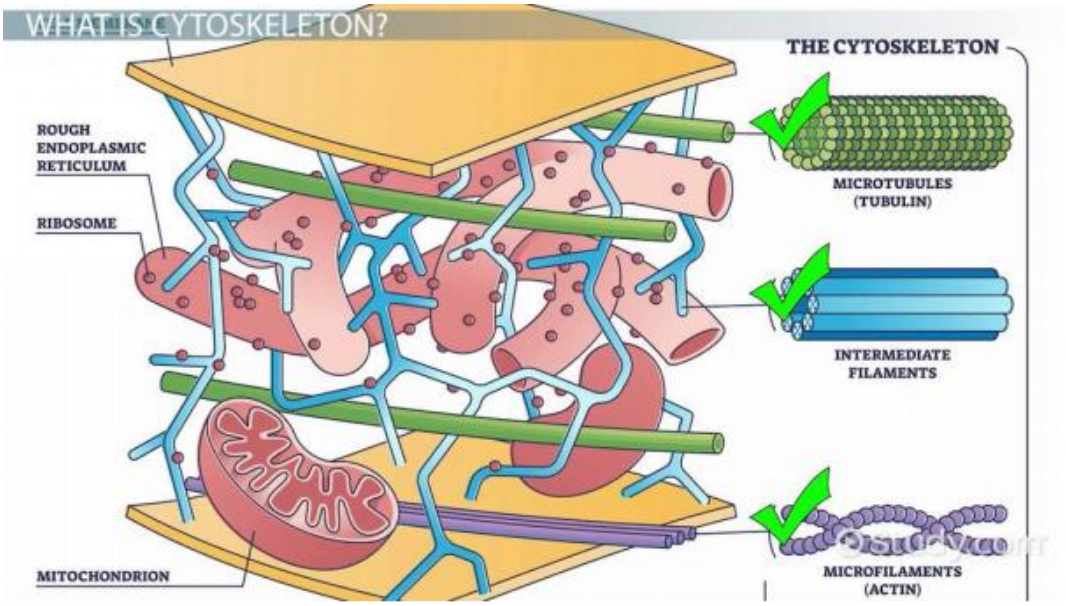

Figure 17 Schematic diagram of the composition of the cytoskeleton

5. Cell adhesion and extracellular matrix

Cell adhesion is a fundamental process that allows cells to attach to each other and to their environment, particularly the extracellular matrix. This ability to adhere is essential for the formation and maintenance of tissues in the body. It also plays a role in dynamic phenomena such as growth, wound healing and immune response.

Adhesion is ensured by various families of specialised proteins called ***adhesion molecules,*** such as ***cadherins*** (involved in cell-cell junctions), ***integrins*** (which anchor cells to the extracellular matrix), ***selectins*** and proteins of the ***immunoglobulin superfamily***.

These molecules not only enable physical attachment, but also the transmission of signals between the outside and inside of the cell.

The extracellular matrix, which forms the support around cells, plays a key role in these interactions. It is composed of proteins such as collagen, fibronectin and laminin, which serve as anchor points for cells. However, the structure, composition and functions of the extracellular matrix will be studied in more detail in another part of the course.

6. Chromatin, chromosomes and cell nucleus

The nucleus is the most apparent structure in the protoplast of eukaryotic cells, acting as the organizing center of the cell. It is present during the interphase and dissolves during cell division.

The majority of cells contain a single nucleus, generally centered. However, some cells can be binucleate, such as hepatocytes, or multinucleate like muscle cells, which can have up to 100 nuclei. Although the nucleus is usually spherical and centered, it can also present various shapes.

The nucleus is generally centered and spherical, but can also be irregular, plurilobate (as in polynuclis) or macronucleated (as in Stentor). Its size in interphase is proportional to that of the cell, large cells like oocytes having a voluminous nucleus. A relationship exists between the cytoplasmic mass and the mass nuclear, and if the cytoplasm becomes too large, the cell divides. The nucleus can be positioned at the center, as in lymphocytes, fibroblasts and endocrine cells, or moved to the base, as in mucous cells, or located at the periphery, as in muscle cells and adipocytes.

6.1. Structure of the Nucleus

The nucleus is separated from the cytoplasm by a nuclear envelope, which exists only in eukaryotic cells (not in prokaryotic cells). This envelope, derived from the endoplasmic reticulum, forms a complex membrane structure that separates chromatin from the hyaloplasm during interphase and regulates exchanges between the nucleus and the cytoplasm. The nuclear envelope is composed of two membranes, an inner and an outer membrane, separated by a 30 nm gap. It also contains nuclear pores.

The outer membrane can be connected to the granular endoplasmic reticulum (REG), and ribosomes may be present on its cytoplasmic face, as on the REG. The inner membrane is covered by the lamina, a network of proteins (about 2000 types) that provides support for the nucleus and, according to recent studies, participates in the organization of chromatin movements during the different phases of the cell cycle.

The inner and outer membranes of the nuclear envelope fuse at regular intervals to form nuclear pores. These pores have a complex "basketball hoop"-shaped structure (Figure 18) and consist of three rings parallel to the nuclear membrane:

- ✓ The cytosolic ring, located on the outer membrane,
- ✓ The nucleoplasmic ring, located on the inner membrane,
- ✓ A small nucleoplasmic ring, located in the nucleus and connected to the nucleoplasmic ring by filaments.

Perpendicular to these three rings is the central transporter of the pore, which crosses the axis of the canal.

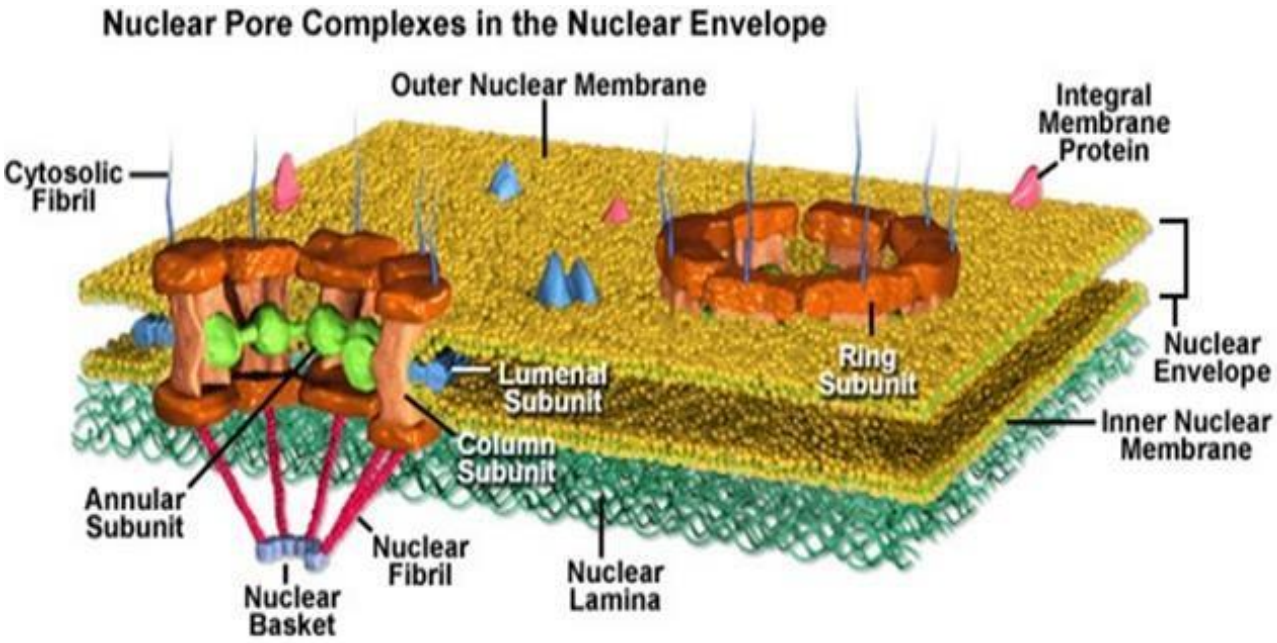

Figure 18: Structure of a nuclear pore

The nucleus contains between 400 and 2000 pores, depending on cell activity. Each pore has a diameter of 100 nm, but its channel has a diameter of 10 nm at rest. During active transport, the pore can change shape and reach a diameter of 25 nm. It regulates the exchange of molecules between the nucleus and the cytoplasm. For example, it allows the entry of nuclear proteins,

proteins regulating gene transcription, as well as enzymes necessary for DNA and RNA synthesis. It also allows the output of RNAs.

The nucleus is made up of a homogeneous nucleoplasm in which one or more nucleoli are bathed. In the nucleoplasm, denser masses are distinguished: chromatin, which appears in the form of filaments connecting denser masses together.

6.2. The chromatin

Chromatin is the form in which DNA is organized in the cell nucleus for most of the cell cycle. During cell division, it condenses to form chromosomes. Chromatin is essential for regulating gene expression and maintaining DNA integrity.

Chromatin is a structure composed of DNA and histone proteins that are specific to eukaryotic cells. The histones are organized into an octamer consisting of two copies of four different types: H2A, H2B, H3, and H4. The DNA, consisting of 146 base pairs, wraps twice around this octamer to form a unit called nucleosome, about 11 nm in diameter. The portion of linear DNA between 2 nucleosomes constitutes the internucleosomal bond. A fifth histone, H1, is located outside the nucleosomes and ensures the stabilization of the nucleosome concatenation, thus facilitating the compaction of DNA.

Two models of chromatin organization in the cell nucleus: ***Heterochromatin*** and ***euchromatin***

• ***Euchromatin***: This is the less condensed form of chromatin, generally associated with actively transcribed regions of DNA, that is to say involved in gene expression.

• ***Heterochromatin***: This form is more condensed and inert, often linked to inactive genetic regions, such as centromeres and telomeres

Chromatin changes: The structure of chromatin can be altered by chemical modifications of histones, such as ***acetylation, methylation or phosphorylation***. These modifications influence the accessibility of DNA and regulate gene expression.

Chromatin performs various functions***:***

1. ***DNA compaction***: Chromatin allows to compact the DNA in the cell nucleus, thus facilitating its storage while maintaining its accessibility for transcription and replication.

2. ***Regulation of gene expression***: The structure of chromatin determines the activation or repression of genes. The euchromatin is more accessible to transcription factors, promoting gene expression, while heterochromatin is often associated with repressed genes.

3. ***DNA repair***: Chromatin plays a key role in DNA repair by facilitating its access to repair enzymes in case of damage

Chromatin is not a fixed structure. It undergoes changes during the cell cycle, notably:

• ***During mitosi***s: Chromatin condenses to form visible chromosomes, facilitating the separation of DNA.

• ***During interphase***: Chromatin exists in a more decondensed form, allowing DNA transcription and replication.

A chromosome is a structure located in the nucleus of eukaryotic cells that contains genetic information in the form of genes. Chromosomes are essential for transmitting genetic information during cell division.

The number of chromosomes varies according to species. In humans, each somatic cell (except gametes) contains 46 chromosomes, or 23 pairs. One of each pair comes from the mother and the other from the father. Gametes (eggs and sperm) are haploid and contain 23 chromosomes, half of the total number of chromosomes.

Chromosomes are responsible for transmitting genetic information. During cell division (mitosis or meiosis), chromosomes replicate and separate to ensure that each daughter cell receives a complete copy of the DNA.

The chromosome consists of several distinct parts that contribute to its organisation and functioning:

1. ***Chromatin***: Chromatin is the form in which genetic material appears when the cell is not engaged in cell division. Before cell division, DNA is in the form of chromatin, a complex of DNA fibers and proteins, mainly histones. When the cell divides, the chromatin condenses to form distinct and visible chromosomes.

2. Centromere: It is a specialized region where two sister chromatids are connected. The centromere plays a key role in chromatid separation during mitosis and meiosis (figure 19).

3. ***Sister chromatids***: A duplicate chromosome is composed of two sister chromatids, which are identical copies of the same chromosome linked by the centromere. These chromatids separate during cell division.

4. Telomeres: These are regions located at the ends of chromosomes, made up of repetitive DNA sequences. Telomers protect DNA from wear and play a crucial role in cellular aging.

In summary, chromosomes are compact and organized structures that contain DNA in cells (figure 20), while chromatin is the more diffuse and functional form under which DNA is organized in the nucleus.

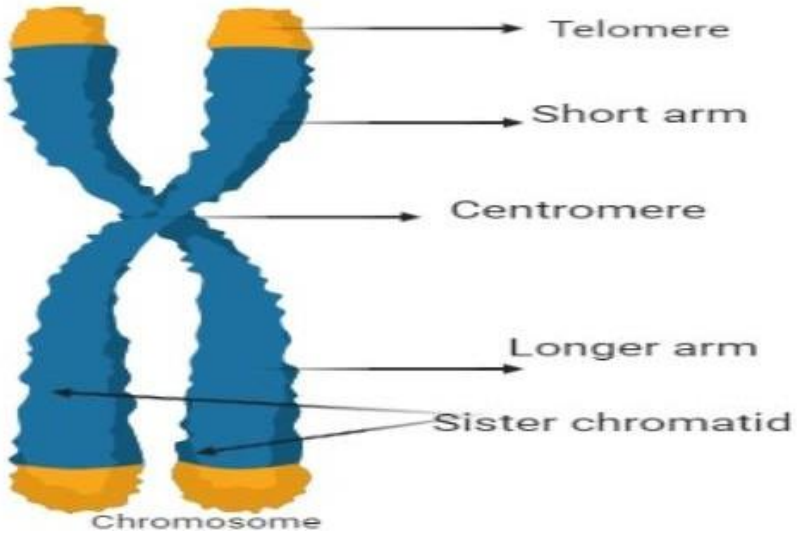

Figure 19: Chromosome structure

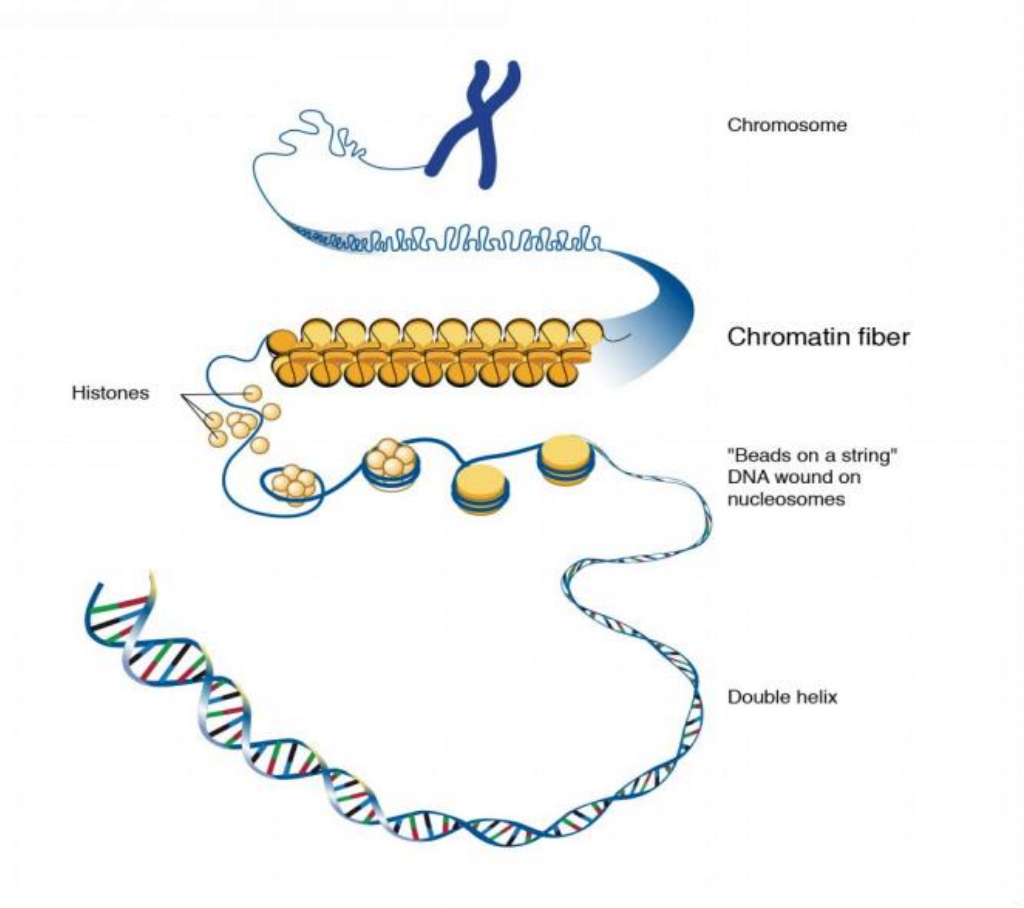

Figure 20: Chromatin, chromosomes and DNA

7. Ribosome and protein synthesis

7.1. Ribosome

The ribosome is a large complex molecular structure, composed of proteins and ribosomal RNA (rRNA). It is the site of protein synthesis in the cell and is found in the cytoplasm, sometimes associated with the endoplasmic reticulum (ER) in eukaryotic cells (formation of the rough endoplasmic reticulum, or RER).

Ribosomes are highly hydrated structures, containing about 70% water, the rest being ribosomal RNA (rRNA) and proteins. The proportion of rRNA and proteins varies depending on the type of ribosome. In eukaryotic ribosomes, the proportions are 50% rRNA and 50% protein, while in prokaryotes they are 40% rRNA and 60% protein.

Ribosomes are structures located mainly on the surface of the endoplasmic reticulum, and their main function is to synthesize proteins by translating the information contained in the messenger RNA. In addition to this essential function, ribosomes also act as a platform for various non-ribosomal proteins, which play a key role in fundamental biological processes, such as the anchoring of the ribosome to cellular organelles and the recruitment of kinases involved in several signaling pathways.

7.1.1. Structure of the Ribosome

The ribosome consists of two subunits (Figure 21):

- ***Major subunit (large)***: Contains the majority of rRNA and proteins. It is responsible for catalyzing the formation of peptide bonds and which ensures the synthesis of the corresponding protein.

- ***Minor (small) subunit***: Also contains rRNA and is involved in reading messenger RNA (mRNA).

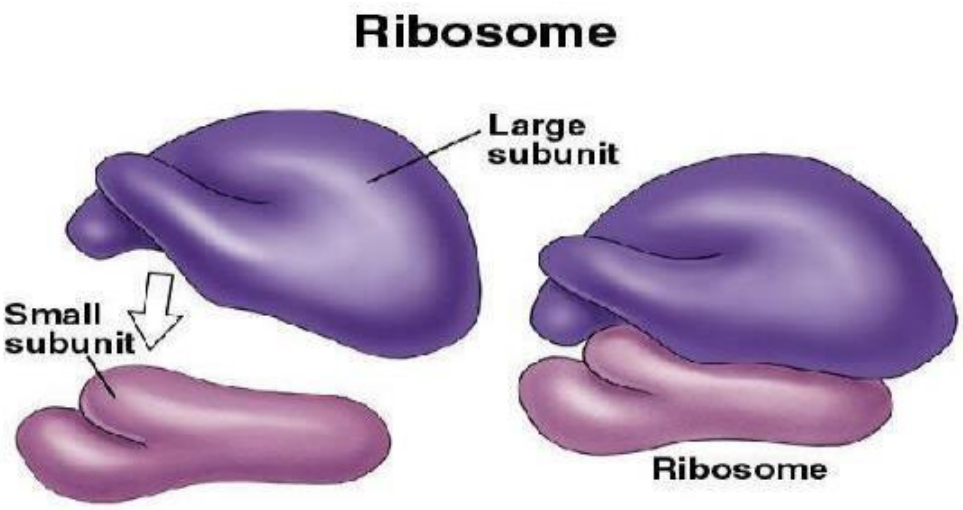

Figure 21: ribosome structure

7.1.2. Location

Ribosomes are found in the cytoplasm, either free or associated with the membranes of the endoplasmic reticulum, nuclear envelope, etc. A set of ribosomes linked to the same messenger RNA strand is called a polysome or polyribosome.

Ribosomes are also present in mitochondria and some plastids, where their structure resembles that of prokaryotic ribosomes.

7.2. Protein synthesis

7.2.1. The process of protein synthesis in eukaryotes

In eukaryotes, the synthesis of proteins takes place in two stages in different compartments (***Figure 22***):

- ***Transcription*** takes place in the nucleus and gives rise to a pre-messenger RNA (pRNA) which undergoes modifications (maturation) to become a mature mRNA to pass through the cytosol (through nuclear pores).

it is about making a copy of an encoded information contained in the DNA molecule into encoded information contained in a messenger RNA molecule.

it is an operation catalyzed by RNA polymerase, after opening and unwinding a portion of the molecule into a double helix of DNA, the enzymatic RNA polymerase complex progresses along the DNA, with incorporation of nucleotides present in the cellular medium. This incorporation occurs through complementarity of the nitrogen bases with one of the strands of the DNA molecule:

- Adenine (A) is placed opposite Thymine (T)
- Uracil (U) is placed opposite Adenine (A),
- Cytosine (C) is placed opposite Guanine (G) and vice versa.

The messenger RNA strand thus synthesized is complementary to the transcribed DNA strand. The information contained in the messenger RNA is identical to that of the untranscribed DNA strand.

- ***The translation*** of mRNA into protein takes place in the cytosol and is carried out by tRNA-aided ribosomes.

it corresponds to the passage of messenger RNA into the cytoplasm to be translated there: it is the synthesis of proteins. It takes place ***in three stages (Figure 23)***:

- ✓ ***Initiation:***

The ribosome recognizes a place in the molecule called **the initiator codon**. Each ribosome formed of two subunits: the small subunit carries a messenger RNA reading site the large subunit has a catalytic site: catalyzes the polymerization of amino acids of the protein

- ✓ ***Elongation:***

The relative displacement of the ribosome and the messenger RNA is accompanied by the progressive elongation of the polypeptide chain; to each triplet of nucleotides of the messenger RNA corresponds an amino acid.

The correspondence between messenger RNA nucleotide triplets and amino acids is carried out according to the principles of the genetic code.

the management of amino acids is done by specific tRNAs (transfer RNA), part of which is fixed on each codon. A peptide bond allows the attachment of each new amino acid (provided by a transfer RNA) to the last amino acid of the chain being elongated. The new amino acid arriving temporarily becomes in turn the last.

- ✓ ***Termination:***

When the ribosome reaches one of the three codons "**stop"** or "**nonsense**", codon to which no amino acid corresponds, the dissociation between the messenger RNA and the completed polypeptide chain begins.

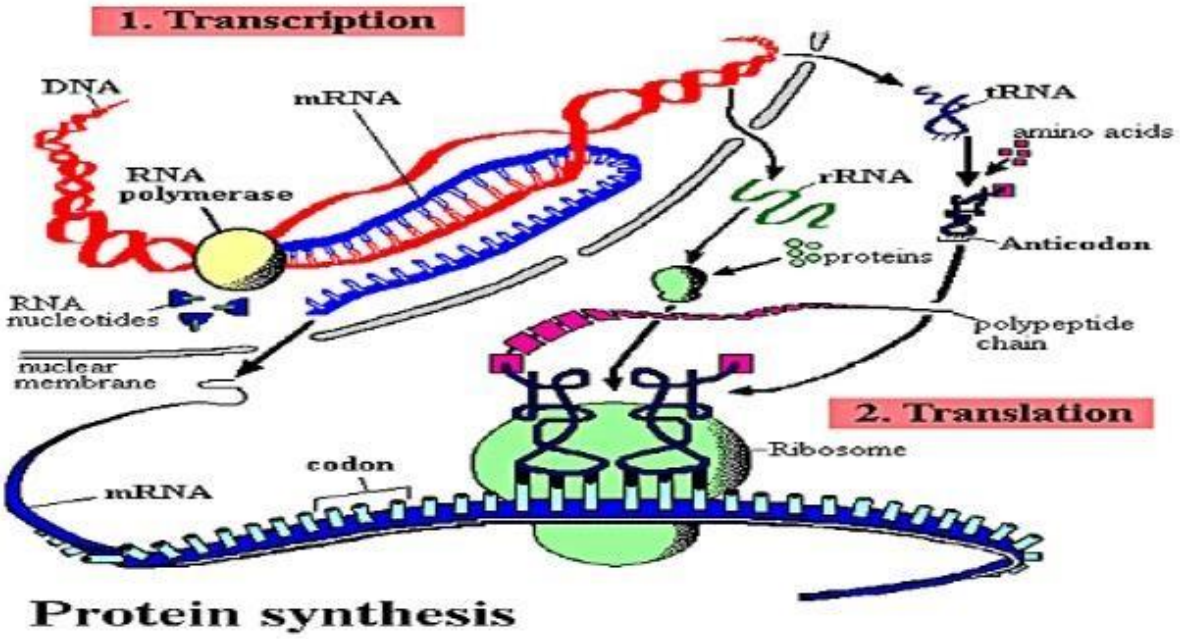

Figure 22: Steps of protein synthesis in a eukaryotic cell.

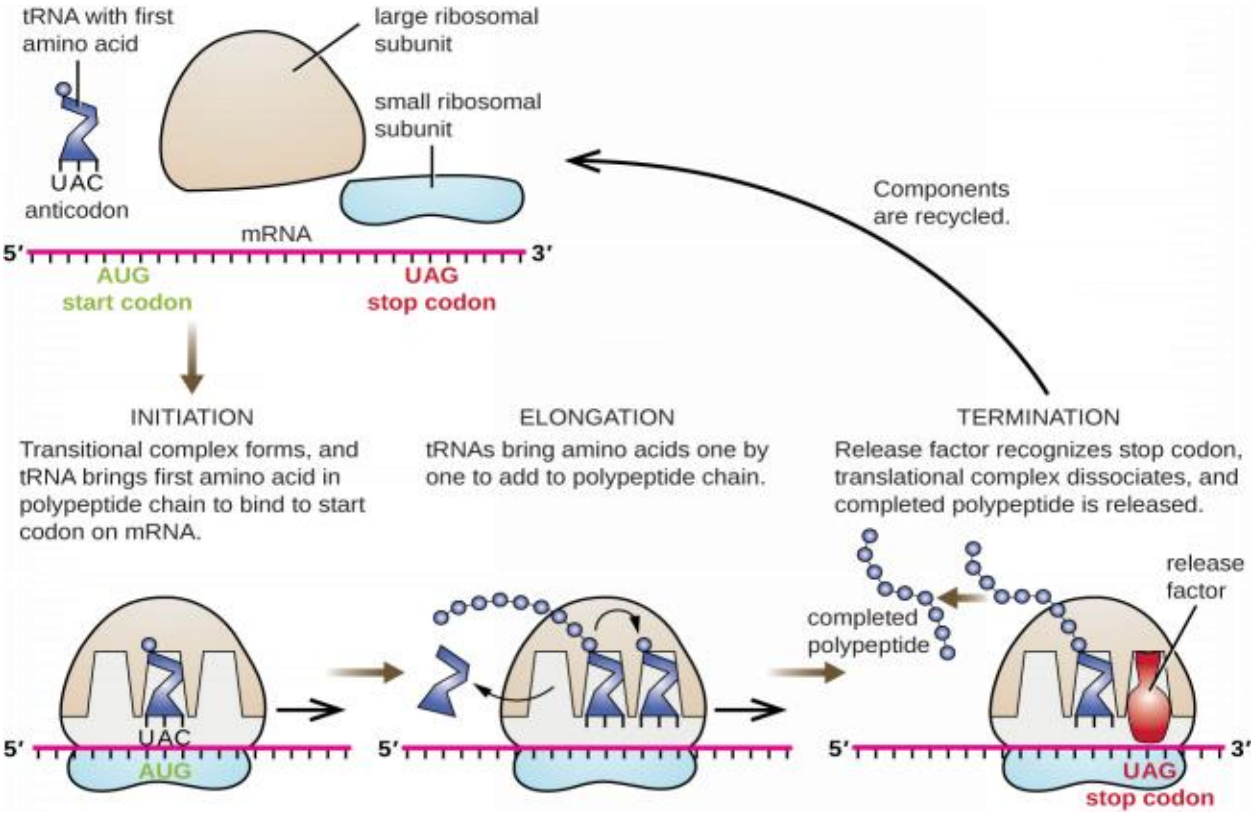

Figure 23: Steps of Translation in a eukaryotic cell.

7.2.2. The Protein Synthesis Process in Prokaryotes

Protein synthesis in prokaryotes follows a similar process to that in eukaryotes, but with differences due to the simplicity of their cellular structure. It occurs in two main stages: transcription, where DNA is copied into messenger RNA (mRNA), and translation, where mRNA is used to synthesize proteins.

In prokaryotes, these two stages are often coupled, occurring simultaneously in the cytoplasm, as there is no nucleus to separate these processes. The mRNA, immediately available after transcription, is translated by ribosomes during its synthesis.

The regulation of protein synthesis occurs primarily at the transcription level, with operons such as the lac operon or the trp operon, which control gene expression depending on environmental conditions.

In conclusion, the synthesis of proteins takes place in two main steps: transcription (DNA RNA) and translation (RNA protein). These steps differ depending on whether the organism is a prokaryote or a eukaryote, due to their cellular structure (Figure 24).

- ***Transcription (DNA → RNA)(table)***

The main points of comparison between prokaryotic and eukaryotic transcription are shown in the table 03.

Table 03: Transcription in prokaryotes vs eukaryotes

Prokaryotes	Eukaryotes
RNA ready to be translated directly	RNA must be modified
	cap, poly-A tail, splicing)

Translation (ARN_m → Protein)

The main points of comparison between prokaryotic and eukaryotic translation are shown in the table 04.

Table 04: Translation in prokaryotes vs eukaryotes

Prokaryotes	**Eukaryotes**
Starts at the same time as the transcription	Starts after RNA exits the nucleus
polycistronic mRNA (several proteins)	monocistronic mRNA (single protein)
First amino acid: formyl-methionine (fMet)	First amino acid: methionine (Met)

The synthesis of proteins:

Prokaryotes: fast, simple, everything happens in the cytoplasm.

Eukaryotes: more complex, nucleus/cytoplasm separation, RNA maturation.

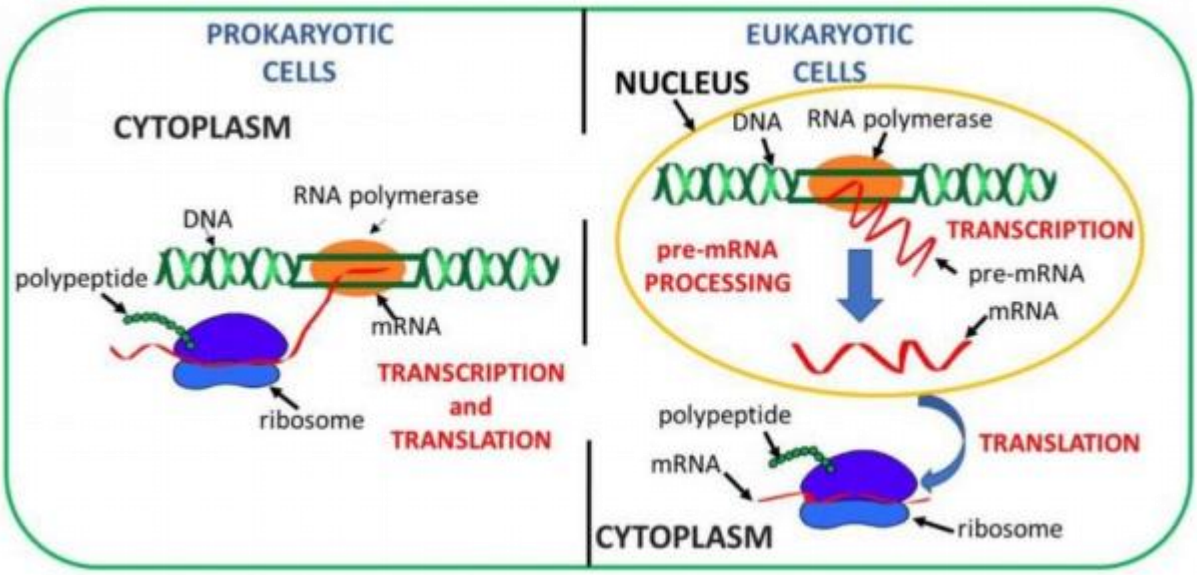

Figure 24: Steps involved in protein synthesis in prokaryotic (left) and eukaryotic cells (right).

8. The Endoplasmic Reticulum-Golgi System

8.1. The endoplasmic reticulum system

Discovered in 1845 thanks to the progress of optical microscopy, the endoplasmic reticulum constitutes a network of cavities in the cytoplasm. It is an organelle of eukaryotic cells (absent in prokaryotic cells) whose membrane forms a continuous sheet surrounding an internal space called lumen. It is a set of membranes defining cavities in the form of cisterns or tubules.

Depending on the presence or absence of ribosomes on its membrane, the granular or rough endoplasmic reticulum (REG) is distinguished from the smooth endoplasmic reticulum (REL). The endoplasmic reticulum is connected to the nuclear envelope and maintains exchanges with the Golgi apparatus and the plasma membrane.

The rough endoplasmic reticulum is composed of flattened cavities, delimited by membranes filled with ribosomes. Most often in continuity with the nuclear envelope.

While **the smooth endoplasmic reticulum** is composed of tubules, canalicules, and circular cavities, lined with smooth membranes.

- ***Structure of the endoplasmic reticulum***:

The endoplasmic reticulum is formed by a set of intracellular cavities of various shapes, such as canals, tubules, vesicles, and flattened vacuoles (Figure 25). The membranes that delimit this network have one side in contact with the cytosol (or hyaloplasm), called the cytosolic side, and another oriented towards the internal space, called the luminal side. These membranes are continuous. A particular type of endoplasmic reticulum, the sarcoplasmic reticulum, is specific to striated muscle cells.

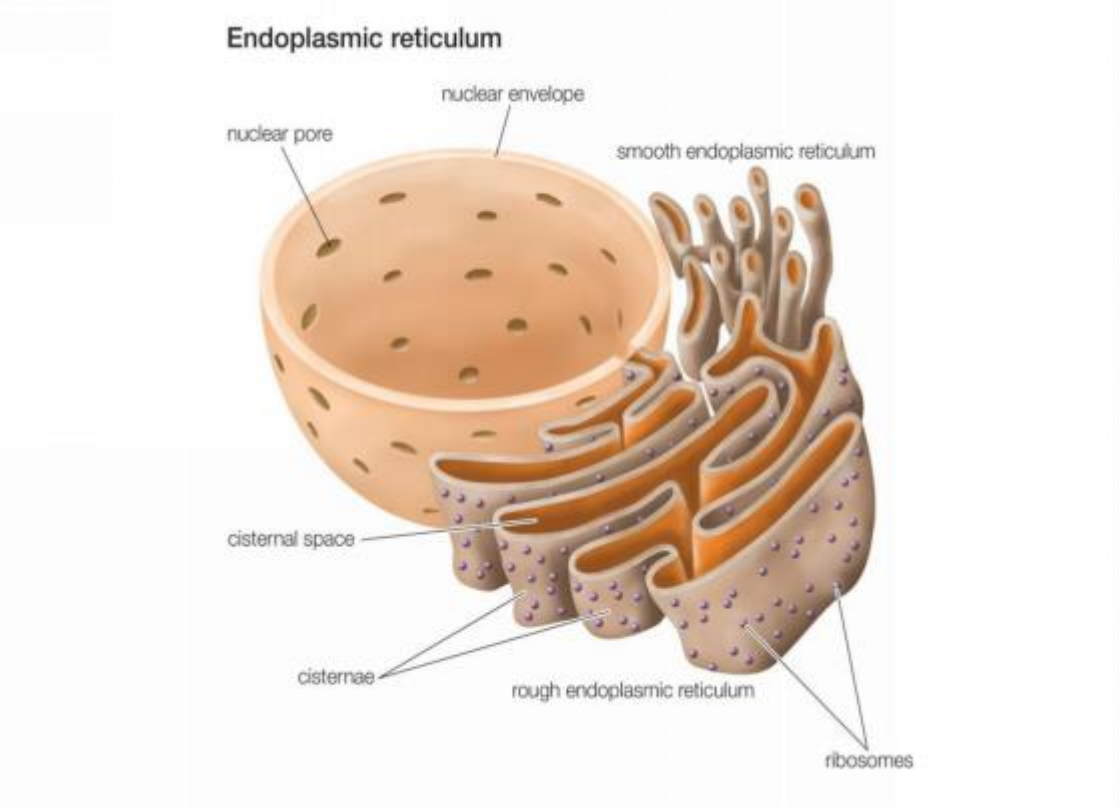

Figure 25: Structure of the Endoplasmic Reticulum

- ***Chemical composition***:

The endoplasmic reticulum membrane is composed of approximately 70% proteins (such as glycosyltransferase, cytochrome P450, and glucose-6-phosphatase) and 30% lipids. Phospholipids form a lipid bilayer, rich in unsaturated fatty acids, which gives the membrane great fluidity. Cholesterol is present in small amounts. Carbohydrates, also in small amounts, are attached to proteins and lipids, and are found on the luminal side of the membrane. This membrane has a fluid and asymmetrical mosaic structure.

The content of the cavities of the reticulum is an aqueous solution dominated by a mixture of proteins: holoproteins, glycoproteins, lipoproteins. The content of the endoplasmic reticulum cavity differs from cell to cell. For example, in cells of the exocrine pancreas, the REG cavity contains enzymatic proteins, the REL cavity in luteal cells contains steroid hormones, and the sarcoplasmic reticulum of muscle cells stores calcium (Ca++).

- ***Functions of REG:***

The main functions of the REG are:

- ✓ ***Translocation of soluble proteins: quality control of newly synthesized soluble proteins leading to their maturation***:

The granular endoplasmic reticulum (***REG***) ensures quality control of newly synthesized proteins. These proteins contain an ER-targeting signal, consisting of 16 to 30 hydrophobic amino acids. This signal is recognized by a cytoplasmic signal recognition particle (SRP), which binds to it and directs the SRP-signal complex to the ER membrane. The ribosome, bound to the translocon, then binds to this membrane to allow translocation of the protein into the ER.

- ✓ ***Protein Glycosylation: Transformation of a Protein into a Glycoprotein***

Glycosylation is a process that transforms a protein into a glycoprotein, and it occurs only for proteins synthesized in the endoplasmic reticulum. There are two types of glycosylation: O-

glycosylation and N-glycosylation, the latter being the most common. In N-glycosylation, the asparagine of the protein is modified.

A fatty acid called dolichol, synthesized in the cytoplasm, is inserted into the membrane of the endoplasmic reticulum. There, it forms a chain of 14 sugars, composed of N-acetylglucosamines, mannoses, and glucoses, which is transferred to the asparagine of the protein by a glucosyltransferase.

- ***Functions of the REL:***

The main functions of the REL are:

- ***Biosynthesis of membrane phospholipids***:

The smooth endoplasmic reticulum (REL) plays a crucial role in phospholipid biosynthesis, thanks to the presence of enzymes involved in lipid metabolism (such as transferases, phosphatases, and decarboxylases) in its membranes.

It constitutes the main source of phospholipids for cell membranes. These phospholipids are synthesized by transmembrane enzymes whose active site is directed toward the cytosol, then distributed throughout the bilayers through the action of ŀipases. The latter, integrated into the REL membrane, transfer phospholipids from the cytosolic hemimembrane to the luminal hemimembrane. Synthesis of steroid hormones.

- ***Calcium storage***:

All cells have specialized REL cisternae to store calcium. In striated or cardiac muscle cells, where Ca++ is crucial for contraction, the REL is highly developed and called the sarcoplasmic reticulum. Ca++ crosses the REL membrane using an ATPase (calcium pump). It is then stored in the cavity by calsequestrin, a binding protein, before being released into the cytosol through calcium channels during muscle contraction.

- ✓ ***Detoxification***:

The REL contributes to detoxification using cytochromes P450, enzymes present on its membranes, which employ NADPH and O2 to treat exogenous drugs and certain metabolites.

These substances, often fat-soluble, are integrated into the membrane of the REL, where they are hydroxylated by cytochromes P450, which makes them hydrophilic. They are then transferred into the lumen of the REL, then eliminated from the cell by exocytosis after having been neutralized and solubilized.

- ✓ ***Biosynthesis of steroid hormones:***

In REL, steroid hormones are synthesized, such as sex hormones (estrogen, progesterone, testosterone) and hormones secreted by the adrenal glands, like cortisone

- ***Conclusion: Role of the REG and the REL***

The rough endoplasmic reticulum (***REG***) plays a key role in protein synthesis, especially those destined for export, integration into the membrane, or delivery to organelles. It is covered with ribosomes, which gives it its "rough" appearance.

The smooth endoplasmic reticulum (***REL***), which lacks ribosomes, is involved in lipid synthesis, carbohydrate metabolism, detoxification of toxic substances, and calcium storage (particularly in muscle cells).

Thus, the **REG** and the **REL** work together to ensure the production and processing of molecules essential to the cell.

8.2. The Golgi apparatus

This organelle is located near the nucleus, close to the pericentrosomal material. It was discovered in 1898 by the Italian researcher Golgi while examining nervous tissue. It is part of the endomembrane system. It consists of stacks of flattened saccules, associated with numerous vesicles.

8.2.1. Structure

The Golgi apparatus is made up of various elements (Figure 26):

- ✓ **The dictyosome**:

The dictyosome is formed by a stack of saccules, which are the basic structural units. These saccules are associated with vesicles and tubules. In a cell, several dictyosomes (from 3 to 10, depending on the cellular synthesis activity) are connected to each other by tubules, thus forming the entire Golgi apparatus.

- ✓ **Faces:**

Each dictyosome has two distinct faces:

• ***The cis face***, located on the rough endoplasmic reticulum (RER) side,

• ***The trans face***, located on the other side, is concave and oriented toward the secretory vesicles (in secretory cells) and the plasma membrane.

Each dictyosome is surrounded by vesicles that transport RER proteins from the cis face to the trans face, all the way to the plasma membrane.

- ✓ **Vesicles:**

Vesicles form by budding from saccules. They are surrounded by a mantle whose composition varies depending on the type of vesicle.

- ✓ **The cis region:**

The cis region consists of the cis-Golgi network (GCN) and the cis saccules, as well as the vesicles that circulate between the RER and the GCN. Vesicles bud from the RER and travel to the GCN, covered with a coatomer (different from the clathrin coat).

These vesicles ensure transport between the RER and the GCN, which, in turn, delivers the products received to the cis saccules via coatomer vesicles.

- ✓ **The medial region:**

This region contains a variable number of saccules and vesicles. It is responsible for the transformation of secretory products and their transport to the trans saccules.

- ✓ **The trans region:**

The trans region consists of a concave saccule, oriented toward the plasma membrane, and is associated with the trans-Golgi network (TGN). Two types of vesicles emerge from the GTN:

• ***Clathrin-coated vesicles***, which travel to two possible destinations:

- ✓ **To the plasma membrane**, where they contain secretory granules (as part of the exocytosis-controlled secretion of specific molecules).
- ✓ **To other compartments**, such as endosomes or lysosomes, by fusion with transport vesicles.

• **Naked vesicles**, which transport non-specific products as part of constitutive exocytosis, before fusing with the plasma membrane.

The Golgi apparatus is a series of flattened sacs called cisternae, stacked on top of each other, often surrounded by vesicles.

It has a polarized organization with a cis (receiving, close to the endoplasmic reticulum) face and a trans (sending, towards the membrane or other organelles) face.

This structure allows the Golgi apparatus to modify, sort, and transport proteins and lipids produced by the reticulum, sending them to their final destination within or outside the cell.

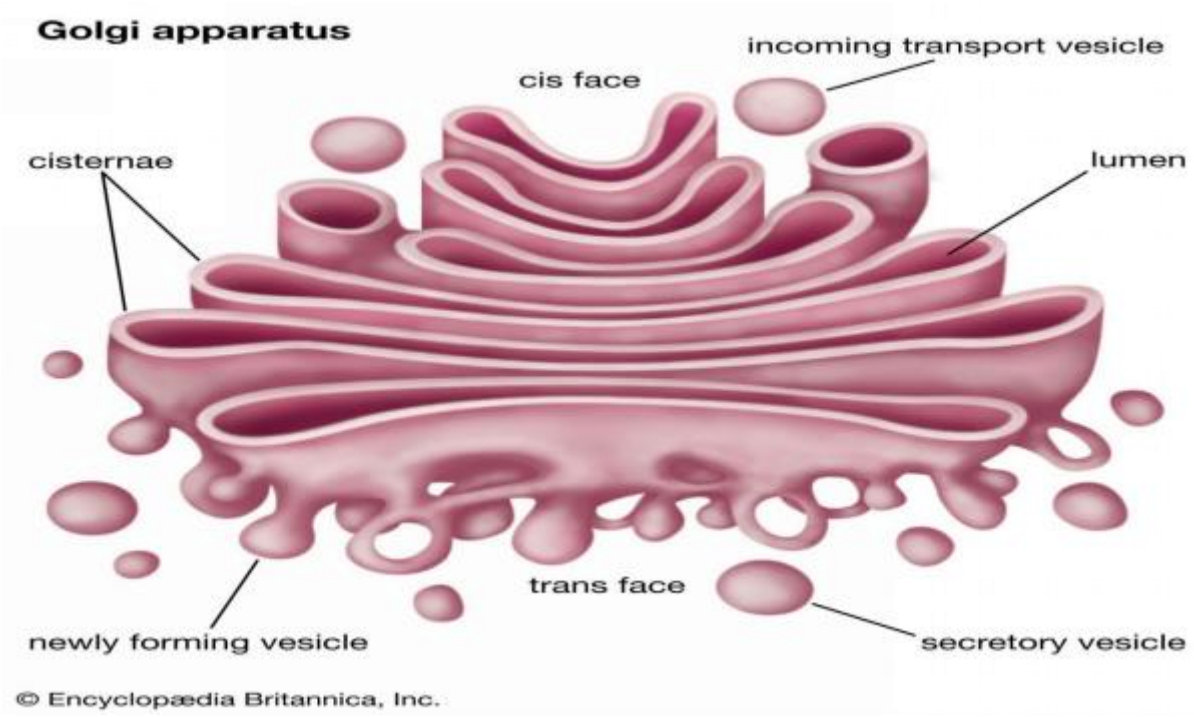

Figure 26: Golgi apparatus structure

8.2.2. Chemical composition

The Golgi apparatus contains 35% phospholipids and 65% proteins, the majority of which are enzymes, particularly phosphatases.

The Golgi membrane has a structure similar to that of unit membranes, with two dense leaflets and one clear leaflet. It is richer in lipids than the endoplasmic reticulum membrane, but less than the plasma membrane (30% for the RER, 35% for the Golgi, and 40% for the plasma membrane).

It also contains numerous enzymes in the form of proteins embedded in the lipid bilayer.

8.2.3. Physiological role

The Golgi apparatus performs several functions

- ***Glycosylation***:

Glycosylation, particularly O-glycosylation, occurs primarily in the Golgi apparatus, where glycosyltransferases in its membranes add sugars to proteins and lipids.

This process results in the formation of glycoproteins and glycolipids, with the sugar attaching to the oxygen of the amino acid, such as serine or threonine.

- ***Sulfation:***

Sulfation consists of the addition of one or more sulfate radicals to glycoproteins, through the action of sulfotransferases present in the Golgi membrane, as is the case for sulfated mucopolysaccharides.

- ***Protein transfer and packaging:***

Protein transfer and packaging illustrate the interaction between the Golgi apparatus and the endoplasmic reticulum. Polypeptide chains synthesized in the granular endoplasmic reticulum are transferred to the cis-face of the Golgi apparatus via transition vesicles.

They are then packaged into secretory vesicles on the trans-face. These vesicles fuse to form secretory granules that are released into the extracellular environment by exocytosis, during which the vesicle membranes fuse with the plasma membrane.

- ***Storage:***

Proteins, such as hormones and enzymes, are transferred into secretory vesicles where they are concentrated and stored until their release into the extracellular environment.

- ***Biosynthesis of polysaccharides***:

Polysaccharides, such as cellulose and glycogen, are synthesized in the Golgi apparatus. Cellulose contributes to the formation of the pecto-cellulosic (or skeletal) wall of plant cells.

The Golgi apparatus consists of a stack of flattened sacs called cisternae, organized in a polarized manner (cis-face and trans-face).

Thanks to its structure, it performs essential functions: modification, sorting, and transport of proteins and lipids produced by the endoplasmic reticulum. It plays a key role in cellular secretion, lysosome formation, and intracellular transport.

9. The interphase nucleus

The nucleus is an organelle specific to eukaryotic cells, surrounded by a nuclear envelope that isolates it from the cytoplasm. It contains the nucleoplasm, where mainly the chromatin is located as well as one or more nucleoles.

As the cell's true control center, it regulates all of its activities through DNA. The main component of chromatin, DNA carries the genes responsible for genetic inheritance.

The nucleus in interphase, observed under the microscope after staining, appears as a clearly visible oval structure, measuring between 10 and 20 micrometers. It is surrounded by a membrane and occupies about 6% of the total cell volume. It is one of the most complex organelles of the cell, and even today, certain aspects of its functioning remain poorly understood.

However, advances in electron microscopy since the 1950s, as well as genomics and fluorescence microscopy techniques (notably the confocal laser microscope), have made it possible to better study it, especially from the 1970.

The interphase nucleus is a complex but essential structure. It manages genetic information, regulates cellular functions, and coordinates the activities necessary for cellular life. Its study is constantly evolving thanks to technological advances.

The interphase nucleus is composed of four main elements (Figure 27):

1. ***Nuclear envelope***: Double membrane surrounding the nucleus, the outer membrane of which is continuous with the rough endoplasmic reticulum. It is pierced by numerous

nuclear pores (1000 to 4000) which regulate exchanges between the nucleus and the cytoplasm. It protects DNA while allowing the passage of RNA and proteins.

2. ***Nucleoplasm***: A fluid substance filling the nucleus. It contains chromatin, the nucleole(s), as well as various enzymes and proteins.

3. ***Chromatin***: Diffuse form of DNA associated with proteins (histones).

Two types:

• ***Euchromatin***: decondensed, active (expressed genes)

• ***Heterochromatin***: condensed, inactive (silent genes)

It constitutes the support of genetic information.

4. ***Nucleolus (es)***: Dense, membrane-free area responsible for the synthesis of rRNA and the formation of ribosomal subunits. It is particularly active in growing cells.

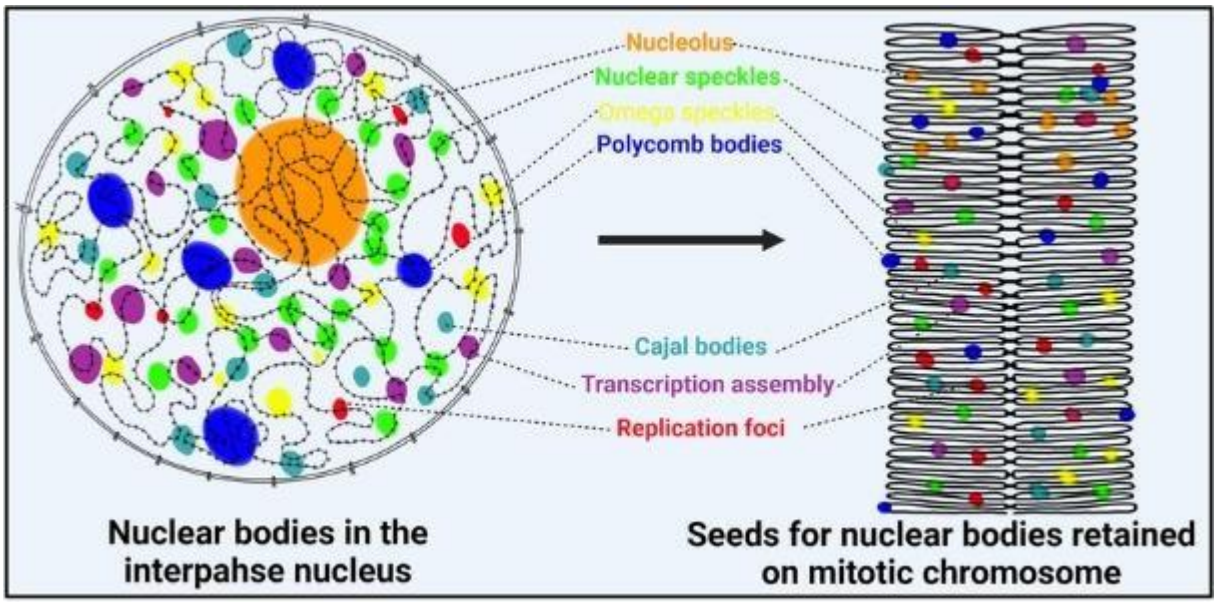

Figure 27: Ultrastructure of interphase nucleus

9.1. Functions of the interphase nucleus

The interphase nucleus performs several functions:

- ✓ ***Storage of genetic information***: The DNA contained in chromatin carries all the genes necessary for the cell to function.
- ✓ ***Regulation of gene expression***: The nucleus controls which genes are expressed, when and in what quantity.
- ✓ ***Synthesis of RNA by DNA transcription:***

messenger RNA (mRNA): leaves the nucleus to be translated into proteins.

ribosomal RNA (rRNA) and **transfer RNA (tRNA):** involved in protein synthesis.

- ✓ ***Production of ribosomes***: Assembly of ribosomal subunits in the nucleolus.
- ✓ ***Cell cycle control***: The nucleus plays a key role in regulating the phases of the cell cycle (interphase, mitosis...).

In conclusion, the interphase nucleus is the cell's command center. It houses the genetic material, controls cellular functions, and prepares the cell for division. It controls all cellular activities (growth, metabolism, differentiation). It enables the hereditary transmission of genetic information during cell division. It plays a central role in responding to extracellular signals, adapting gene expression.

10. The Endosomal System: Endocytosis

Eukaryotic cells possess a specific intracellular transport system that allows the passage, circulation, sorting, and degradation of various molecules.

This system relies largely on:

• **Endocytosis**: the mechanism for the entry of material from the outside of the cell into the inside.

• **The endosomal system**: a set of organelles involved in the sorting, transport, and recycling of endocytosed elements.

10.1. Endocytosis

- ***Definition and role***

Endocytosis is a vesicular transport to the interior of a cell. It is an active cellular process by which the cell internalizes substances (nutrients, receptors, viruses, etc.) by encompassing them in vesicles formed from the plasma membrane.

Endocytosis is a fundamental process for the eukaryotic cell, allowing the controlled entry of external materials. It is closely linked to the endosomal system, which ensures the sorting, distribution and degradation of these materials. This complex system ensures cellular balance and is essential for many physiological and immune functions.

- ***Roles of endocytosis***

The mechanisms of ***endocytosis*** aim to regulate the composition of plasma membrane lipids and proteins, to regulate the interaction of cells with their environment and thus constitute a fundamental support for cellular physiology and homeostasis.

The term ***endocytosis*** was used by Christian deDuve in 1963 to include in the same term the ingestion of large particles and the absorption of fluids or macromolecules in small vesicles.

Endocytosis allows the cell to ingest molecules, liquids or even whole particles, by enclosing them in membrane vesicles formed from the plasma membrane.

Endocytosis performs several specific functions:

- ✓ ***Cellular nutrition***

Allows the introduction of nutrients, such as lipids or proteins, that the cell cannot transport through conventional channels or transporters.

- ✓ ***Immune defense (phagocytosis)***

Immune cells (such as macrophages) use endocytosis to encompass and digest pathogens (bacteria, viruses, dead cells).

- ✓ ***Membrane receptor regulation***

Membrane receptors can be internalized, deactivated or recycled via endocytosis. This regulates the sensitivity of the cell to certain signals (such as hormones or neurotransmitters).

- ✓ ***Transport of specific macromolecules***

Certain molecules such as cholesterol (via LDL lipoproteins) are transported specifically by receptor-mediated endocytosis.

- ✓ ***Cellular communication***

It participates in the entry of signals or messenger molecules, allowing the cell to respond to its environment

Endocytosis follows a precise sequence of steps, ranging from recognition of the substance to its internalisation and intracellular processing:

- ✓ ***Recognition***: extracellular ligands bind to specific receptors on the plasma membrane.
- ✓ ***Invagination***: the membrane forms a pocket that sinks.
- ✓ ***Budding***: the pocket closes to form a vesicle.
- ✓ **Formation of the endocytic vesicle**: the vesicle enters the cytoplasm.
- ✓ ***Fusion with endosomes***: the vesicle merges with an (early) endosome, where its content is sorted.

There are **three types of endocytosis**:

- ***Phagocytosis (phagosomes):*** the most common mechanism, it involves the introduction of a solid into the intracellular medium. These can be: a large molecule, particle or microorganism, for example; bacteria, atmospheric dust, cells or cellular debris (Figure 28).

During phagocytosis, membrane pseudopodia stretch and surround the contents to be brought into the cell. They then close in on themselves, resulting in the formation of a vesicle. This transports the contents through the cytoplasm to the lysosomes, where their contents are digested.

- ***Pinocytosis***: In this process, the cell incorporates liquids in which proteins can be dissolved (Figure 28). During pinocytosis, an invagination is created in the cell membrane and encompasses the content to be introduced into the cell, resulting in the formation of a vesicle. This one carries out transport in the cytoplasm towards the lysosomes where the digestion of the content takes place. Pinocytosis is used for certain solutes and liquids that cannot be absorbed by diffusion.

- ***Receptor-mediated endocytosis (endosomes)*** begins when receptors accumulate in well-defined regions of the cell membrane. This transport mechanism allows the selective entry of molecules into the cell.

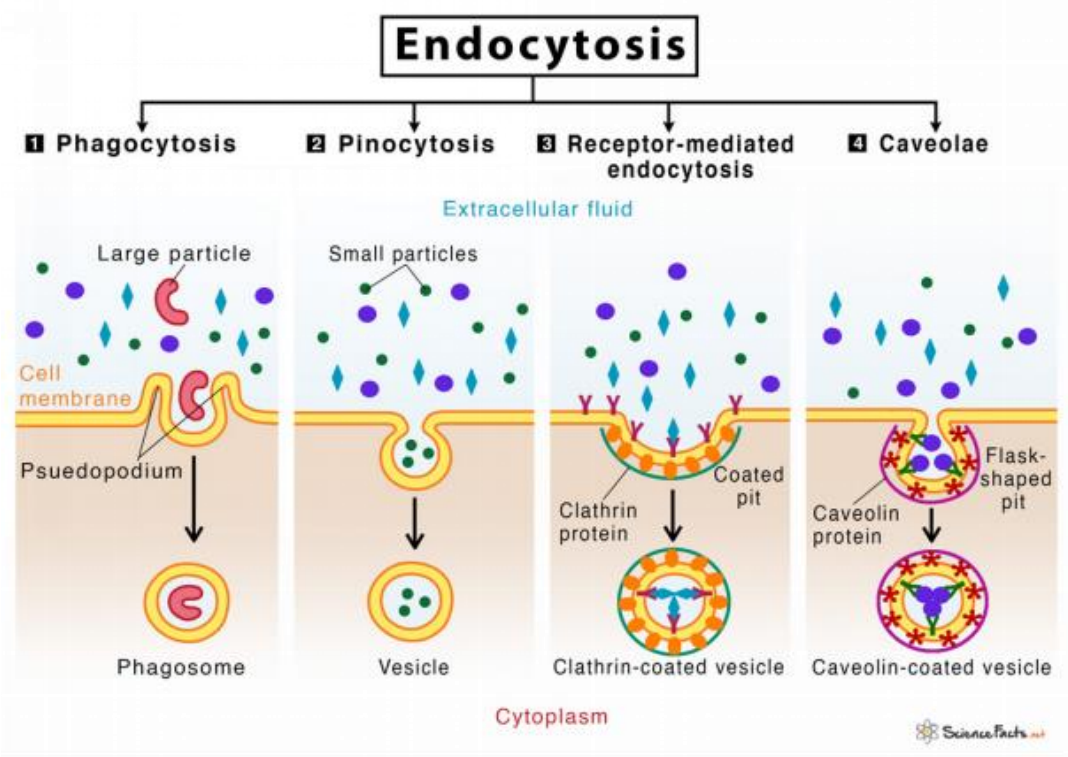

Figure 28. The different modes of endocytosis

10.2. The endosomal system

The endosomal system is a dynamic network of cellular compartments that ensure:

• The sorting of endocytic molecules

• Their recycling towards the plasma membrane

• Their transfer to other organelles (lysosomes).

The endosomal system is composed of early, late, recycling endosomes and lysosomes.

It can be divided into two paths, each characterized by very particular structures:

• **The early endosome pathway** is characterized by sorting endosomes and recycling endosomes.

• ***The late endosome pathway*** is characterized by multi-vesicular bodies.

10.2.1. The path of early Endosmoses

The early endosomes pathway is the first to intervene after endocytosis, that is to say the entry of certain vesicles into the cell from the membrane. These vesicles come from the covered wells (specialized areas of the membrane).

• ***Sorting endosomes:***

The sorting endosomes contain an acidic environment, produced thanks to pumps called H+ ATPases. This acidity allows the separation of ligands (transported molecules) from their receptors. The pH thus gradually decreases from 7.4 (as in the extracellular environment) to about 6.5 in deeper endosomes.

The sorting of molecules is done thanks to the particular shape of the endosome, which is both spherical and tubular. The large molecules remain in the round part, while the smaller ones go into the tubules.

• ***Recycling endosomes***

Recycling endosomes have a different shape: they are mainly connected tubules. They allow the receptors that were captured with the vesicles to be returned to the membrane. On the other

hand, ligands (transported molecules) take a different path, towards other compartments of the cell to be treated or destroyed.

10.2.2. The late endosomal pathway

Late endosomes, which have a pH of about 6.5, are not simply an evolution of sorting endosomes. These are actually new specific compartments in the cell.

They have a particular structure: these are large vesicles that contain smaller vesicles inside. We call this set a multivesicular body. These structures play a role in the degradation of proteins, thanks to special enzymes called hydrolases. These enzymes come from the Golgi apparatus and are transported to late endosomes by vesicles.

Then, the late endosome can follow two different paths, but which lead to the same result: the formation of a lysosome, a compartment responsible for digesting cellular waste:

• either it merges with vesicles containing digestive enzymes (from the Golgi), and then becomes a lysosome,

• either he directly unites with a lysosome already formed.

The maturation and recycling of endosomes are key processes of intracellular trafficking, allowing for the regulation of sorting, transport and recycling of internal cell components. After endocytosis, the vesicles fuse with the early endosomes, which act as sorting stations. These early endosomes can either direct their content to late endosomes for further degradation in lysosomes, or to recycling pathways to return certain receptors or membrane proteins to the plasma membrane or Golgi apparatus. Endosomal maturation involves gradual changes in their lipid composition, pH (increasingly acidic), as well as the replacement of certain protein markers (such as the transition from Rab5 to Rab7). This process ensures a correct orientation of the endocytic content according to cellular needs, ensuring a balance between degradation and recycling, fundamental for the maintenance of cell homeostasis.

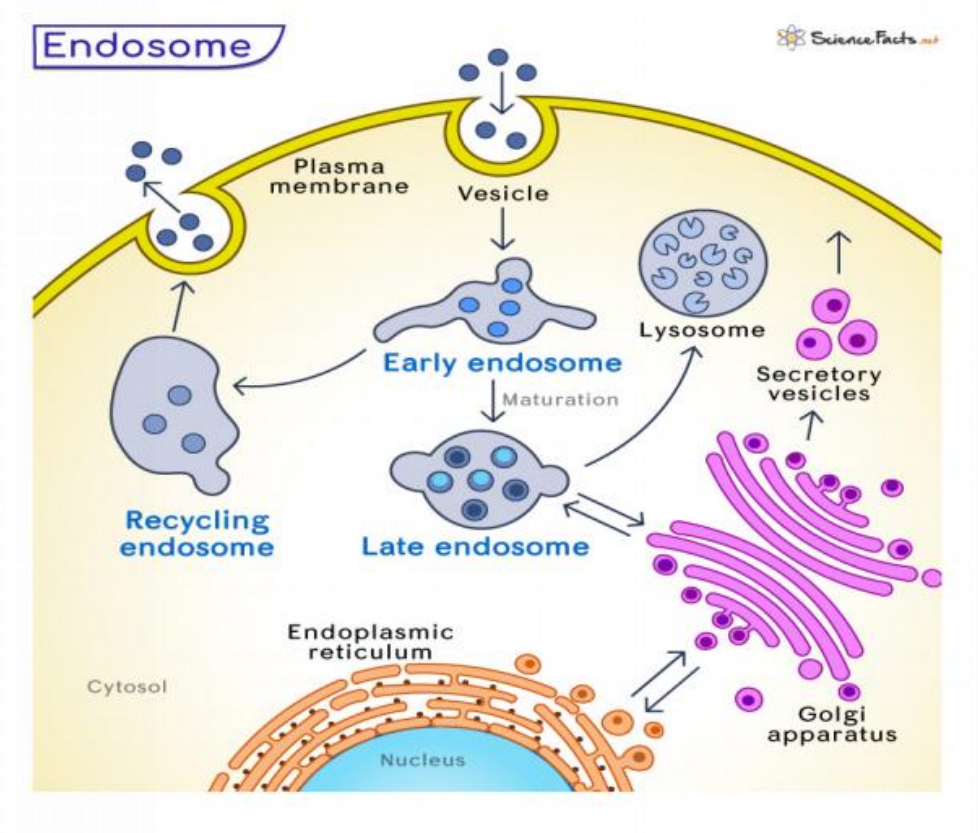

Figure29: Endosome maturation and recycling

11. Mitochondria

The mitochondrion is a cytoplasmic organelle delimited by two membranes, present in all cells of eukaryotic organisms. It plays a central role in the regulation of life and cell death. This organelle is particularly abundant in cells with constant energy requirements, such as muscle cells or hepatocytes**.**

The mitochondrion is composed of an outer membrane, an intermembrane space, an inner membrane, and a central matrix. In addition, the mitochondrion has its own genome, consisting of DNA, and contains all the mechanisms necessary for protein synthesis, including RNAs, ribosomes and specific enzymes.

Of variable shape (spherical or in sticks), it is dispersed in the cytoplasm and its number varies from one cell to another, going from a few mitochondria in yeasts to several thousand in hepatocytes.

11.1. Structure

Electron microscopic examination reveals that mitochondria are organelles delimited by two membranes. The outer membrane, in direct contact with the cytosol, has a unitary membrane structure. The inner membrane, on the other hand, forms invaginations called mitochondrial ridges, where oxidation-phosphorylation reactions take place.

During these reactions, ATP synthase exploits the electrochemical gradient of protons generated by the respiratory chain to produce ATP.

The two membranes are separated by a clear intermembrane space, the thickness of which may vary. The inner membrane defines an internal space called the mitochondrial matrix (figure 30).

The outer membrane of mitochondria is composed of 40% lipids and 60% proteins. Lipids are mainly phospholipids, with a small proportion of cholesterol. The proteins that make it up are mainly enzymes, such as thiokinases, involved in lipid metabolism. This membrane is permeable to molecules of less than 5 kDa, thanks to the presence of porins, which facilitate passive transport. It also contains translocases, protein transporters essential for the import of proteins into the mitochondria

The surface area of the inner membrane is five times larger than that of the outer membrane, due to mitochondrial ridges.

It is composed of 20% lipids and 80% proteins, without cholesterol. Lipids are mainly phospholipids, notably cardiolipids. The majority of proteins in this membrane are components of the respiratory chain, including electron transporters such as cytochromes, ubiquinones (or coenzyme Q), and ATP synthase.

This membrane also houses various transporters involved in the passage of molecules such as pyruvate, fatty acids, ATP, ADP and hydrogen phosphate (H PO), essential for the production of ATP.

Electron carriers facilitate redox reactions, with some transporting both electrons (e^-) and protons (H^+)—these are hydrogen carriers, such as ubiquinone. Others, such as cytochromes (cyt a, cyt a3, cyt b, cyt c, cyt c1), transport electrons exclusively.

The inner membrane also contains translocases, protein transporters responsible for importing proteins into the mitochondria.

The intermembrane space contains enzymes, the most important of which is adenyl kinase, which converts AMP (Adenosine monophosphate) into ATP. First, ADP then crosses the mitochondrial membrane using specific transporters and is phosphorylated into ATP.

AMP +ATP ⟶ 2ADP

The matrix space contains a high concentration of many enzymes, including those involved in the oxidation of pyruvate and fatty acids (to acetyl-CoA), as well as in the citric acid cycle.

There is also DNA, representing the mitochondrial genome, as well as the proteins necessary for its transcription and the translation of mRNA into proteins. However, mitochondrial proteosynthesis is limited to a small number of proteins (13), with the majority of mitochondrial proteins (about 300 different proteins) being imported from the cytoplasm.

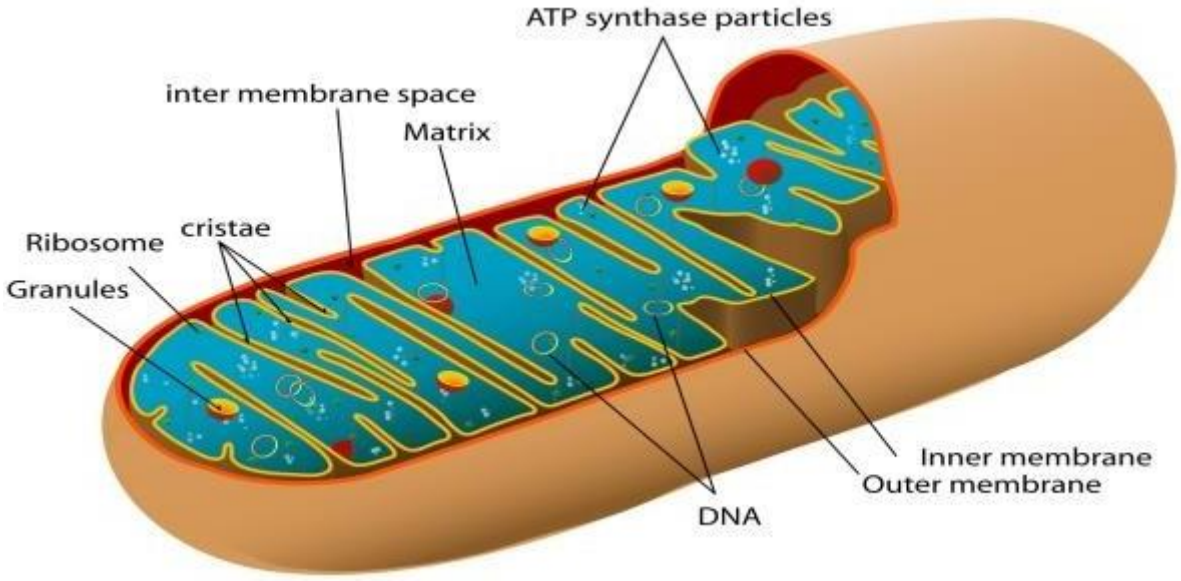

Figure 30: Simplified structure of a mitochondrion

11.2. Physiological roles

- ***Energy production in the form of ATP***

Energy in eukaryotic cells is mainly produced in the form of ATP, either by fatty acid oxidation or glycolysis. The production of ATP by oxidation of energy substrates is a key process in cellular respiration.

- ***Oxidative phosphorylation***

Oxidative phosphorylation is the process by which ADP is converted into ATP, a compound with high energy potential, through phosphorylation. This phenomenon is coupled with oxidation, which means that the production of ATP directly depends on the transfer of electrons, and therefore on the oxidation of energy substrates.

- ***Respiratory chain***:

The respiratory chain consists of several protein complexes located in the inner membrane of the mitochondria. It is responsible for oxidative phosphorylation. Electrons, coming from oxidized molecules (fatty acids or glucose), are transferred along these complexes.

This electron transfer generates a proton (H) gradient across the mitochondrial inner membrane, thus creating a proton-driving force used to synthesize ATP.

- ***ATP synthase (Fo-F1 ATPase)***

ATP synthase is an enzyme that allows the synthesis of ATP using the energy generated by the proton gradient. It consists of two main sub-units:

- ✓ **F_o** : an intra-membrane subunit that serves as a proton channel, allowing protons to pass from the intermembrane space to the mitochondrial matrix.
- ✓ **F_1:** a subunit located in the mitochondrial matrix, responsible for the synthesis of ATP. The passage of protons through ATP synthase allows the conversion of the electrochemical gradient energy into chemical energy in the form of ATP.

- ➢ ***Calcium Storage in Mitochondria:***

Mitochondria, in collaboration with the smooth endoplasmic reticulum, constitute the main intracellular calcium reservoirs. They can capture calcium from the cytosol, store it in the mitochondrial matrix, and release it as needed.

This calcium regulation process involves ion channels located in the mitochondrial inner membrane, such as the PTP (permeability transition pore) and Na^+/Ca^{2+} exchangers. The opening of megachannels and the excessive release of calcium into the cytosol are early events that can initiate apoptosis, or programmed cell death.

Mitochondria perform several other essential physiological functions within the cell, including (figure31):

• **Glyconeogenesis**, as well as fatty acid **and amino acid biosynthesis**, using metabolites generated by the Krebs cycle as precursors for various metabolic pathways.

• In collaboration with the smooth endoplasmic reticulum (SER), they participate in the **biosynthesis of membrane phospholipids**.

• They are involved in **the transport of molecules across their membranes.**

• They also ensure the **synthesis of mitochondrial components** necessary for their function

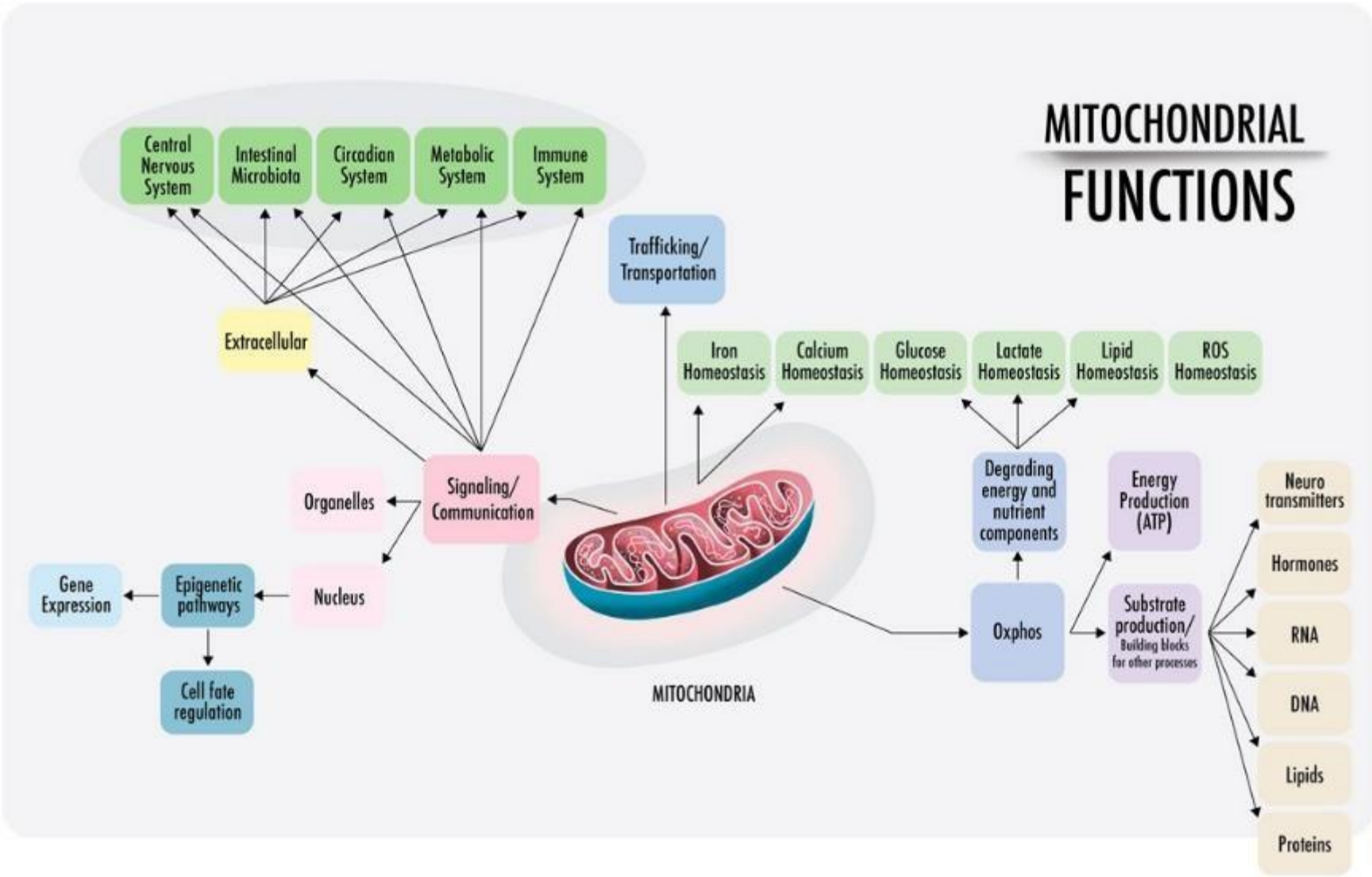

Figure 31: physiological function of mitochondria

12. The Chloroplasts

Chloroplasts are organelles present in the cytoplasm of plant cells, sensitive to different wavelengths of light spectrum, thanks to the chlorophyll they contain. Most of the aerial parts of the plant, notably the leaves, contain chloroplasts, these containing the largest quantity (~ 1⁄2 million per square millimetre of leaf). Chloroplasts play an essential role in photosynthesis, a process that allows plants to feed on carbon and ensure their autotrophy. Each chloroplast originates from a pre-existing chloroplast, and its division occurs during interphase, independent of mitosis.

12.1. Structure of chloroplasts

The chloroplasts are about one micron in size. They generally adopt a flattened disc shape, measuring between 2 and 10 microns in diameter and about 1 micron thick. These organelles are composed of two membranes separated by an intermembrane space. Inside, they contain a membrane network made up of flattened bags called thylakoids, which are immersed in the stroma, a liquid present in chloroplasts (figure 32).

Thylakoids consist of a lumen surrounded by a membrane and contain chlorophyll (green pigment) as well as carotenoids (yellow and orange pigments). A stack of thylakoids forms a granum (plural: grana).

These organelles also contain circular DNA, whose size and structure resemble those of a bacterium, as well as ribosomes, which allows them to duplicate autonomously. Moreover, the stroma contains reserves in the form of starch or lipid droplets.

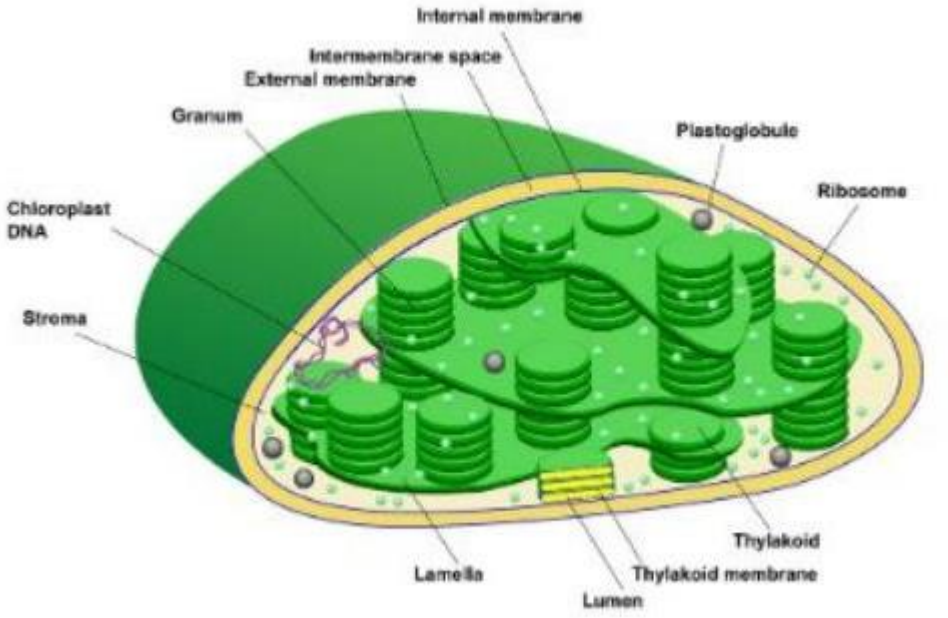

Figure 32: simplified structure of a chloroplast

12.2. Physiological role

- **PHOTOSYNTHESIS**

Photosynthesis is the process by which most plants (including algae) convert light energy into chemical energy (Figure 33).

Photosynthetic organisms are said to be autotrophic: that is to say capable of making their own organic matter using the energy of light origin. They are opposed to heterotrophic organisms (animals, fungi and the majority of bacteria) which draw the energy they need exclusively from already existing organic substances.

In the presence of water and carbon dioxide (CO_2), photosynthetic plants convert light energy into chemical energy and produce sugars (starch).

The mechanism of photosynthesis can be divided into two essential phases, independent in terms of specific reactions but perfectly coordinated with each other thanks to the energy intermediates formed. Photosynthesis can be divided into two stages.

- ***First step "the clear phase"***

The first step consists of a series of light-dependent photochemical reactions, which convert solar energy into chemical energy, stored as ATP and NADPH.

The clear phase of photosynthesis comprises two types of photochemical reactions: ***cyclic photophosphorylation*** and acyclic ***photophosphorylation***, both of which are dependent on light.

- ✓ ***Cyclic photophosphorylation:***

- The excited electrons leave the chlorophyll of the reaction center, pass through a short electron transport chain and return to the reaction center.

- This process leads to the production of ATP by creating an electrochemical gradient, but does not generate either O2 or NADPH.

- The proton motive force produces ATP, without oxygen production.

- ✓ ***Acyclic photophosphorylation***:

- It involves both photosystems (I and II) and their reaction centers (P700 and P680).

- Light energy excites electrons, and photosystem II recovers electrons from water during its photolysis to compensate for the loss of electrons.

- This results in the production of ATP, NADPH, and O_2, with the oxygen being released into the atmosphere and used in cellular respiration.

Both reactions convert solar energy into chemical energy in the form of ATP and NADPH, which will be used in the Calvin cycle for CO_2 fixation.

Primary phase conclusion:

- ✓ PSII and associated complexes are responsible for the release of oxygen into the atmosphere and produce ATP.
- ✓ PSI is responsible for the release of NADPH into the stroma.
- ✓ The ATP and NADPH + H+ molecules formed by cyclic and non-cyclic transport are used by the Calvin cycle (Figure 34): ATP provides energy and phosphate groups, while NADPH + H+ acts as a reducing agent (it is an electron donor).

Each cycle of the Calvin cycle requires 9 ATP and 6 NADPH + 6H

- ➢ ***Second step "the dark phase"***

The dark phase consists of a set of reactions that are not dependent on light (light-independent reactions). It is dedicated to the synthesis of carbohydrates from CO2, using the chemical energy generated during the first phase of photosynthesis.

The dark phase of photosynthesis, which takes place in the stroma of chloroplasts, uses ATP and NADPH produced during photochemical reactions. It is a series of biochemical reactions regulated by enzymes, allowing the reduction and incorporation of CO2 into organic molecules.

The key enzyme in this process is Rubisco, which binds CO2 to RuBP and constitutes up to 16% of total chloroplast proteins. The cycle repeats six times to integrate six CO2 molecules and form one glucose molecule. This glucose will be used in the synthesis of various compounds necessary for the plant, such as polysaccharides, fatty acids, amino acids and nucleotides.

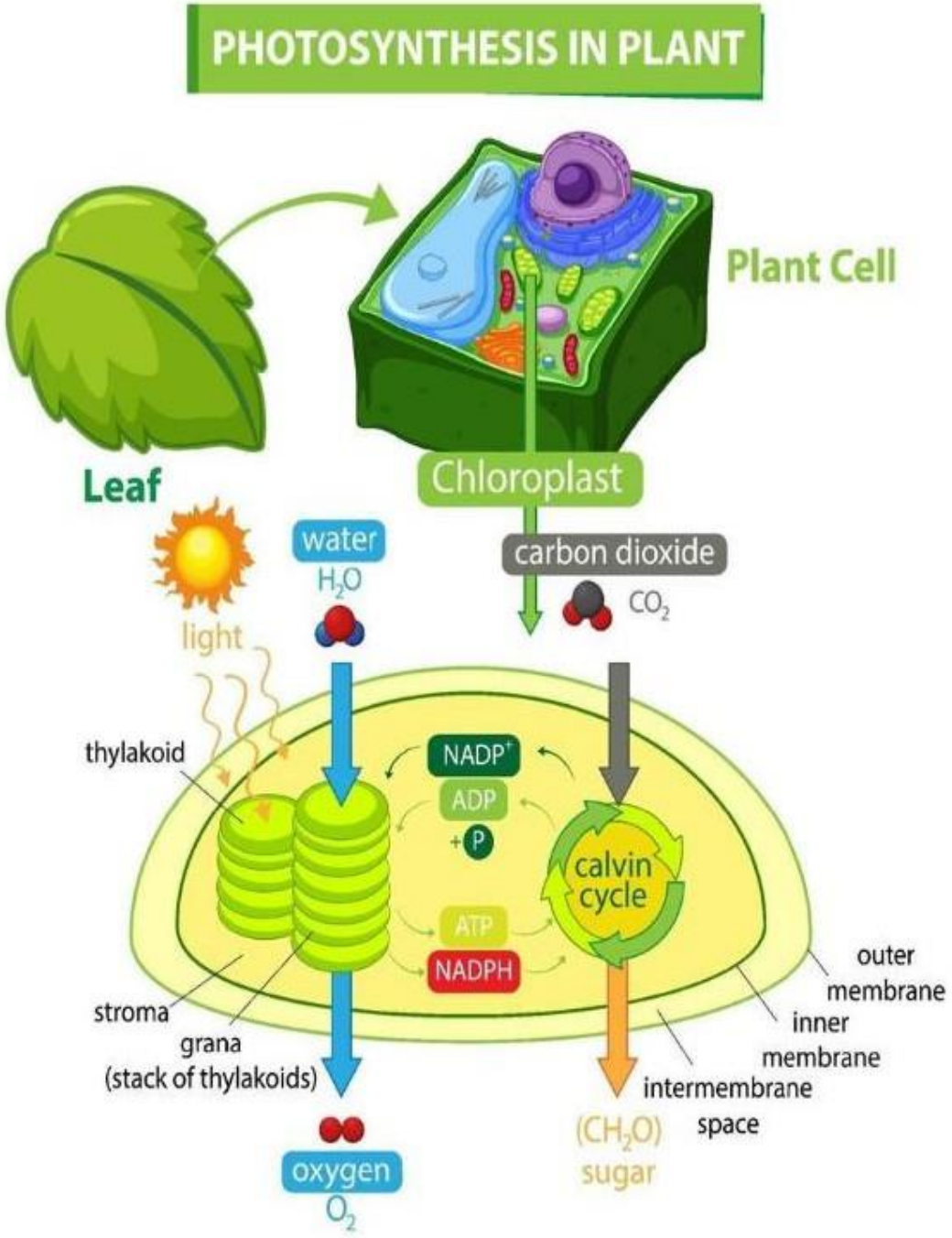

Figure 33: Mechanism of photosynthesis at the chloroplast level

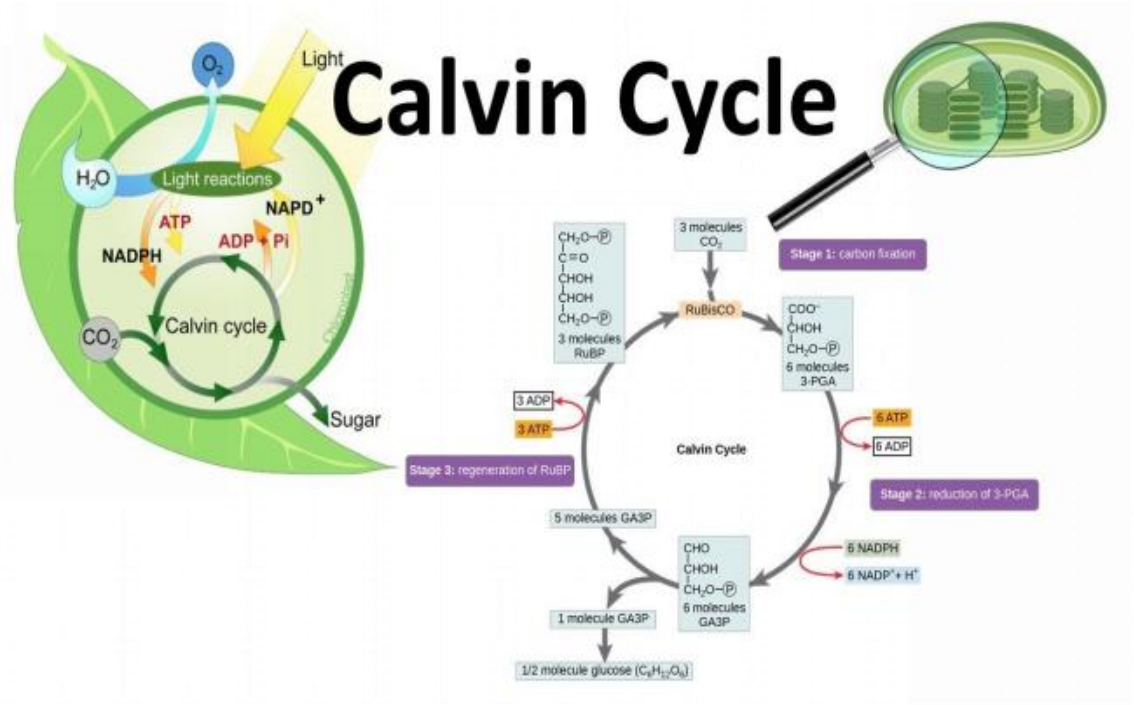

Figure 34: Simplified Calvin cycle

Photosynthesis is an essential bioenergetic process that allows autotrophic organisms, mainly plants, algae and certain bacteria, to convert light energy into chemical energy.

It takes place in two main phases: the photochemical reactions (or clear phase), which take place in thylakoids and produce ATP and NADPH from water and light, and the Calvin cycle (or dark phase), which takes place in the stroma and uses this energy to fix carbon dioxide and produce carbohydrates.

This highly regulated mechanism involves specialized structures (chloroplasts), pigments (such as chlorophyll) and a coordinated set of proteins and enzymes. It plays a fundamental role in maintaining life on Earth by ensuring the production of organic matter and releasing oxygen into the atmosphere.

In summary, ***photosynthesis is the basis of the food chain and planetary biogeochemical cycles***. It perfectly illustrates how plant cells harness solar energy to support not only their own metabolism, but also the overall balance of ecosystems.

13. Peroxysomes

Peroxysomes are cellular organelles surrounded by a simple membrane and containing no genetic material or ribosomes (Figure 36 and Figure 37).

The peroxysome was discovered in the 1950s thanks to the work of Christian de Duve, who identified it as a new cellular organelle during his research on the subcellular fraction containing oxidative enzymes.

In 1965, he officially proposed the term «Peroxysome» to designate this organelle, due to its central role in oxidation reactions generating and degrading hydrogen peroxide (H_2O_2). Initially considered as a simple enzymatic compartment, the peroxisome has been revealed to be a dynamic organelle involved in many metabolic pathways, such as β-oxidation of fatty acids, cellular detoxification or even the metabolism of reactive oxygen species (ROS).

Since its discovery, research has led to a better understanding of its biogenesis, its specific proteins (peroxins) and its involvement in certain rare genetic diseases called peroxysomal disorders, such as Zellweger syndrome.

Peroxysomes are present in all eukaryotic cells (except reticulocytes and red blood cells). These are organelles present in animal and plant cells capable of producing hydrogen peroxide (H2O2).

Their name therefore comes from their ability to produce hydrogen peroxide, or H_2O_2. Peroxysomes are formed by self-replication and not from the Golgi like lysosomes.

These are vesicles containing powerful enzymes capable of neutralizing many toxic substances to the cell using oxygen. These are frequent cellular organelles in liver and kidney cells where they actively contribute to detoxification.

The peroxisomes are constantly renewed. Their lifespan varies depending on the cells. It is 3 to 5 days for hepatocytes. Peroxisomes are not immobile and move in the cytoplasm using microtubules.

The peroxysome contains enzymes such as oxidases, catalase and those of β-oxidation, allowing the detoxification and metabolism of lipids and amino acids.

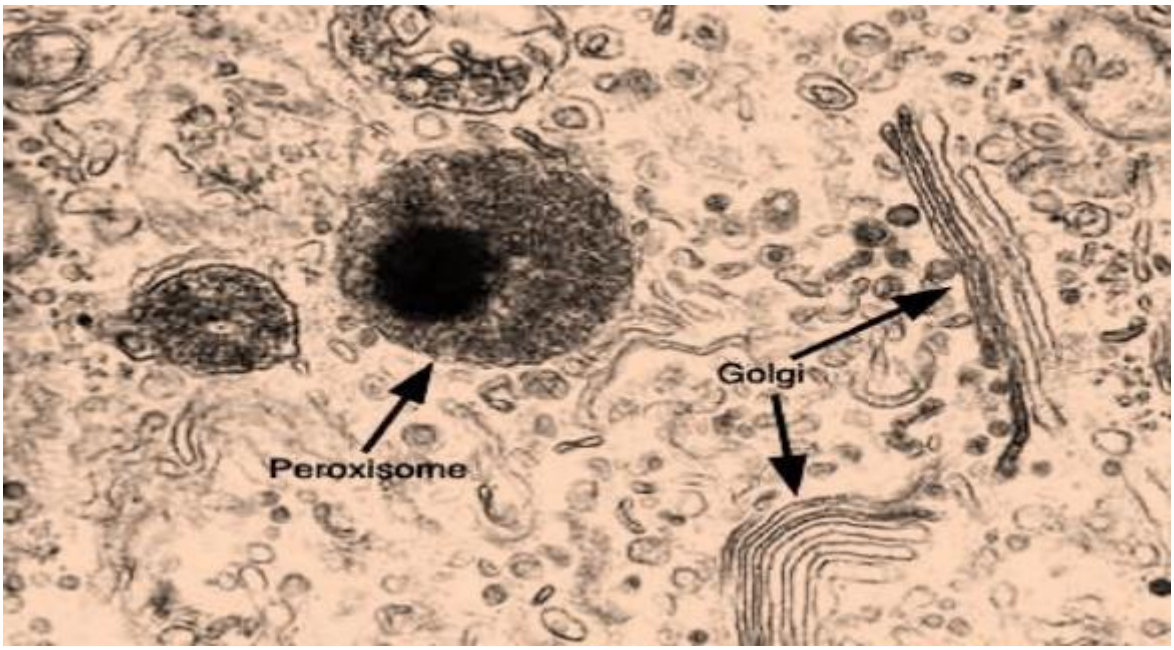

Figure 35: Microscopic observation of peroxysomes inside the cell

13.1. Peroxisome structure

Peroxisomes are visible only under electron microscopy, consisting of a simple membrane of lipid bilayer type, allowing to form a matrix. Inside this matrix, there exists a crystalline nucleus that appears dense to electrons. It is this crystalline nucleus that contains the oxidative enzymes.

These peroxisomes have an ovalous or spherical structure whose size varies from 0.2 to 0.5 μm depending on their activity. The number of peroxisomes varies from one cell to another depending on the type of cell and in the same cell according to the activity of the latter.

It is a network called 'canalicular' independent of the ER, the Golgi and the Mitochondria where each vesicle will be connected to another vesicle by small channels that will allow communication between the different Peroxisomes.

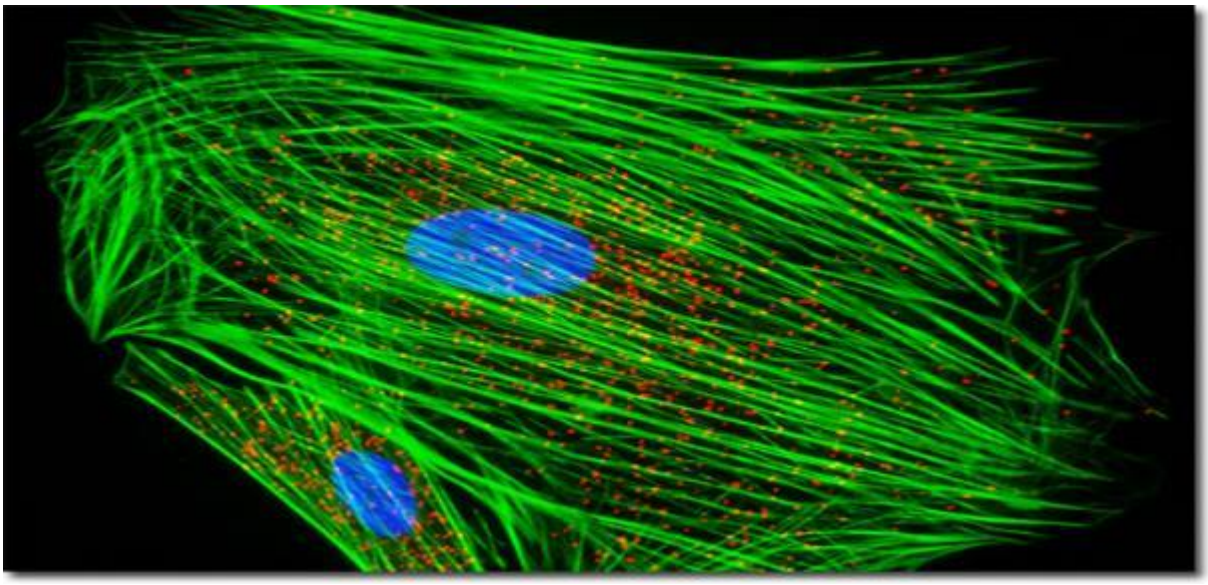

Figure 36: Observation by Immunofluorescence of peroxisome

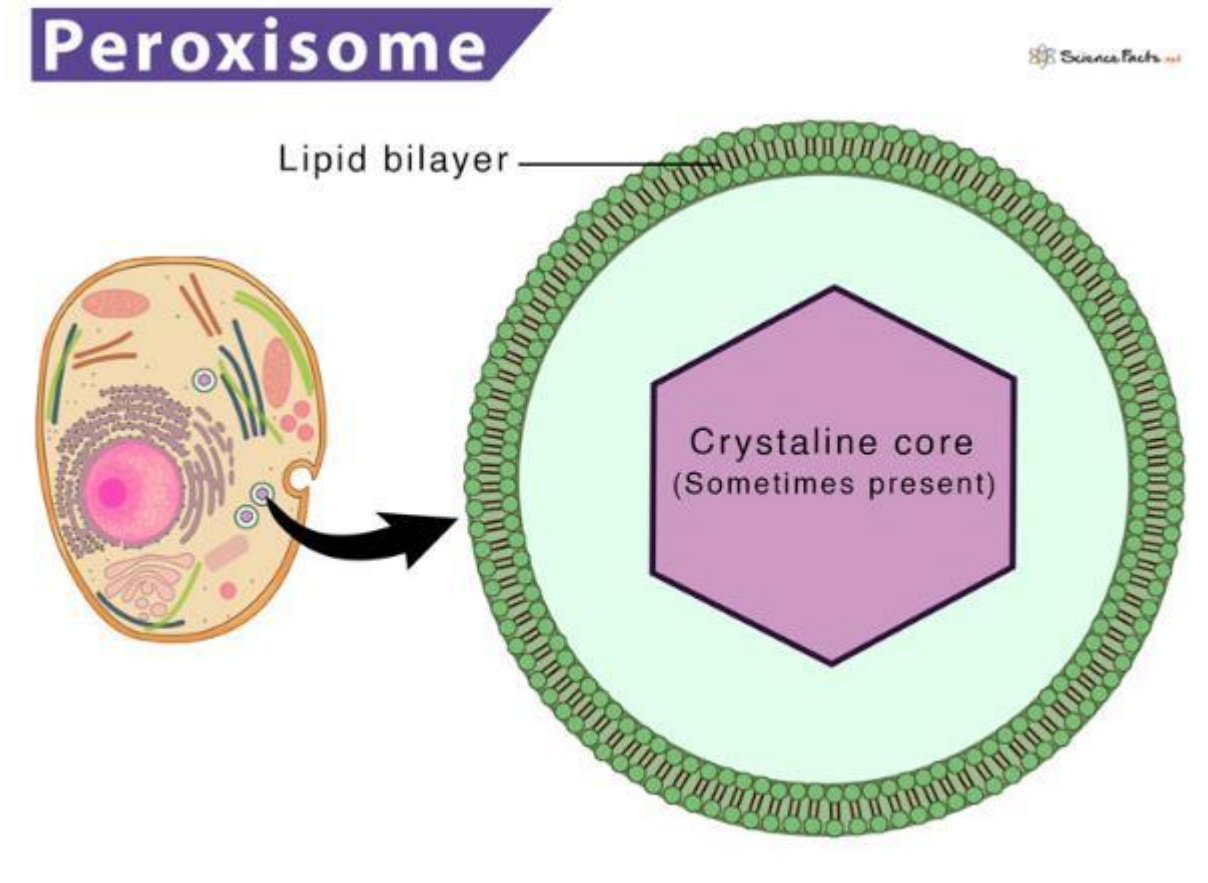

Figure37: Peroxisome structure

13.2. Physiological roles

Peroxisomes are essential sites for the use of dioxygen. They use O_2 and H_2O_2 during oxidation reactions. They provide multiple functions: Anabolic and catabolic (Figure 38).

These are cellular organelles that carry out oxidation reactions using molecular oxygen (O) and thus producing a reactive molecule hydrogen peroxide (H_2O_2), which will be decomposed by means of the catalase enzyme they contain to avoid its toxicity.

Oxidases, enzymes present in the peroxysome, use oxygen to remove hydrogen atoms at specific organic substrates (SH_2), thereby producing oxidized substrate (S) and H_2O_2 depending on the reaction:

$$SH_2 + O_2 + H_2O_2$$

Then it is necessary to eliminate the H2O2 because it is a toxic catabolite, and it is the peroxysome that will itself eliminate the H2O2 thanks to catalasic activity. Indeed, when an excess of H_2O_2 accumulates in the cell, catalase converts H2O2 into H2O (2H2O2= 2H2O + O2).

Catalase uses hydrogen peroxide H_2O_2 generated by other enzymes to oxidize a variety of other toxic substrates R' (phenols, methanoic acid, alcohol): it is called a peroxidation reaction, mainly in the liver and kidney cells.

$$H_2O_2 + R'H_2 \longrightarrow R' + 2\,H_2O.$$

Catalase also catalyzes the reaction:

$$H_2O_2 + H_2O_2 \longrightarrow O_2 + 2H_2O$$

Catalase is the most abundant enzyme in peroxysomes. The other enzymes in the matrix are linked to the degradation of various metabolites.

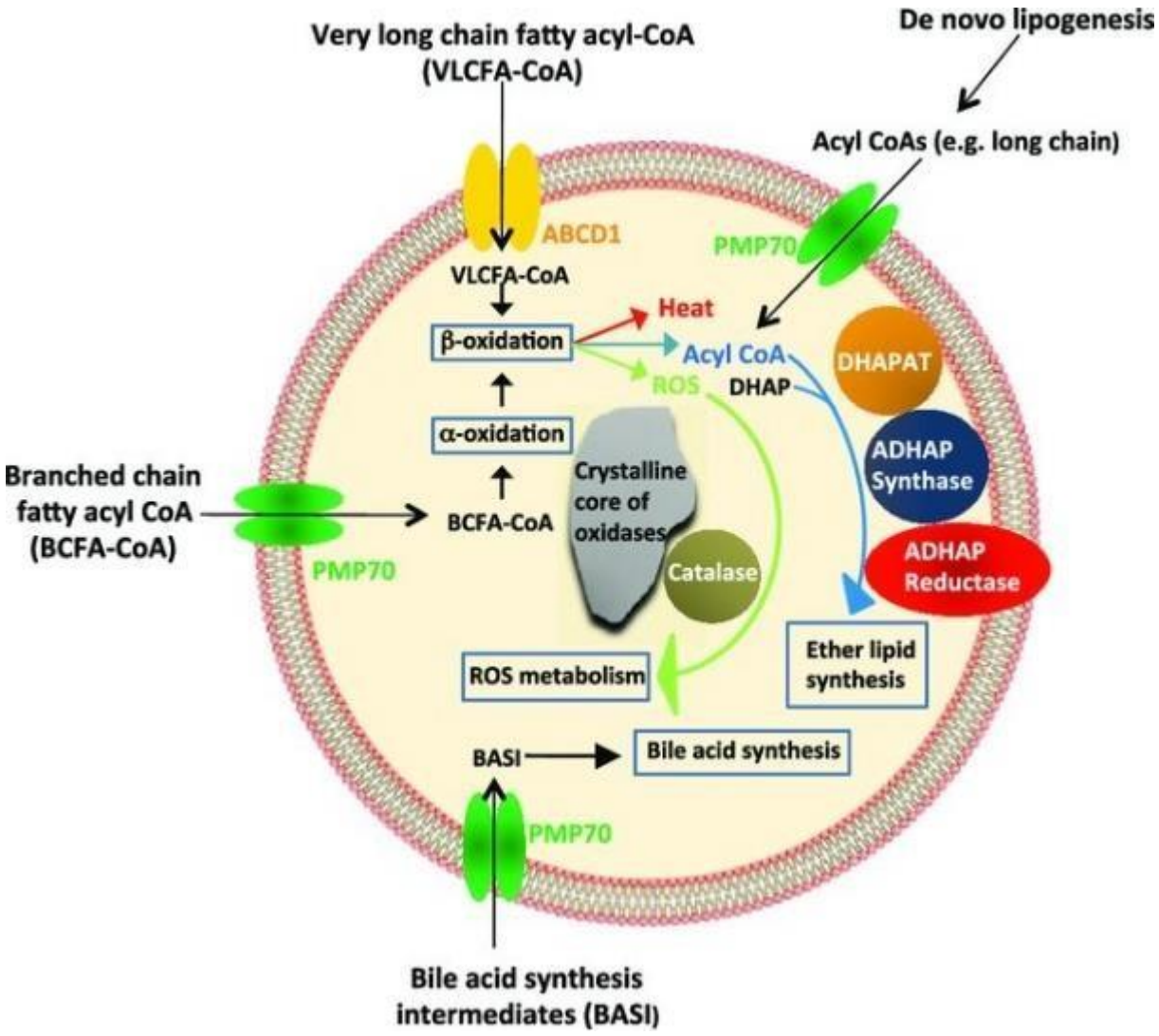

Figure 38 : Functions of Peroxisome

- ✓ ***β oxidation***

Peroxisomes perform the beta-oxidation of long-chain fatty acids by a mechanism similar to that of mitochondria. They even have the exclusivity of this pathway in yeasts and plants.

Nevertheless, the energy balance is reduced to the production of acetylcoenzyme A because the electrons of the reduced coenzymes result in the formation of hydrogen peroxide detoxified on-site by catalase.

✓ ***Photorespiration***

In the leaves of chlorophyllian plants, peroxysomes intervene during photorespiration by involving chloroplasts and mitochondria (figure 39).

photorespiration is based on the oxygenase function of Rubisco and involves the regeneration of an APG molecule from two phosphoglucolic acid molecules.

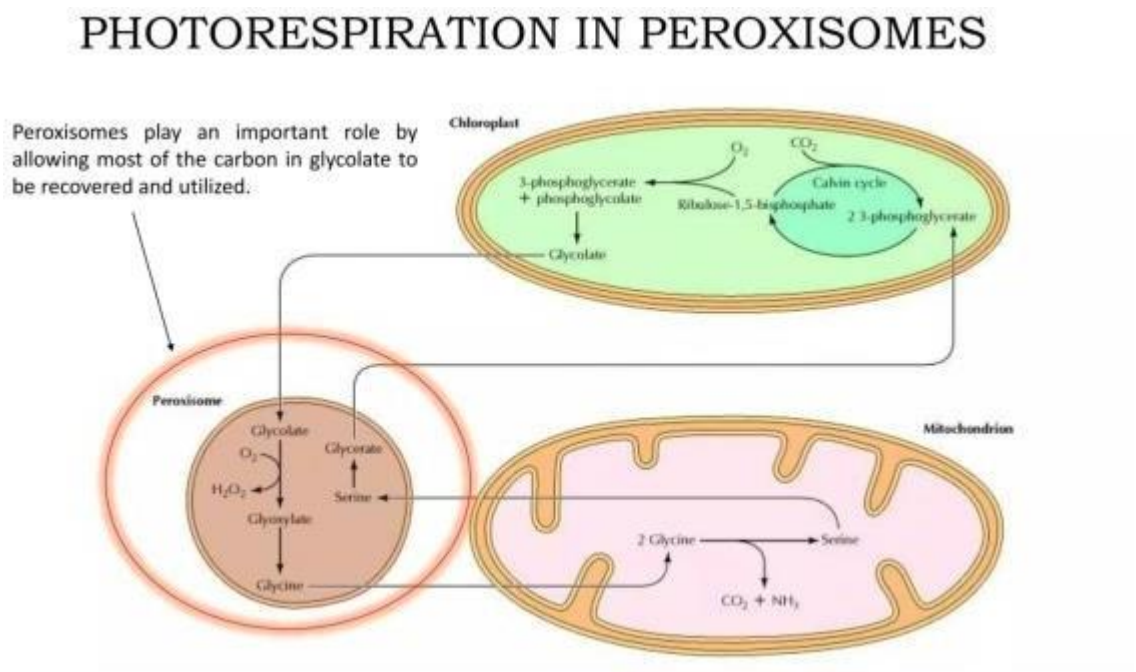

Figure 39: Simple illustration of peroxisomes photosynthesis.

This metabolism of photorespiration involves three cellular compartments (figure 40), the chloroplast, the peroxisome, and the mitochondria, and numerous exchanges of metabolites between these compartments. During the course of this cycle, two molecules of glycolate are metabolized into phosphoglycerate (PGA) with consumption of O_2 and release of CO_2.

Overall, it is indeed a catabolic process with loss of CO_2 and oxygen absorption (gas exchange of respiratory type). Moreover, it is a process that consumes ATP and NADPH provided by the primary reactions.

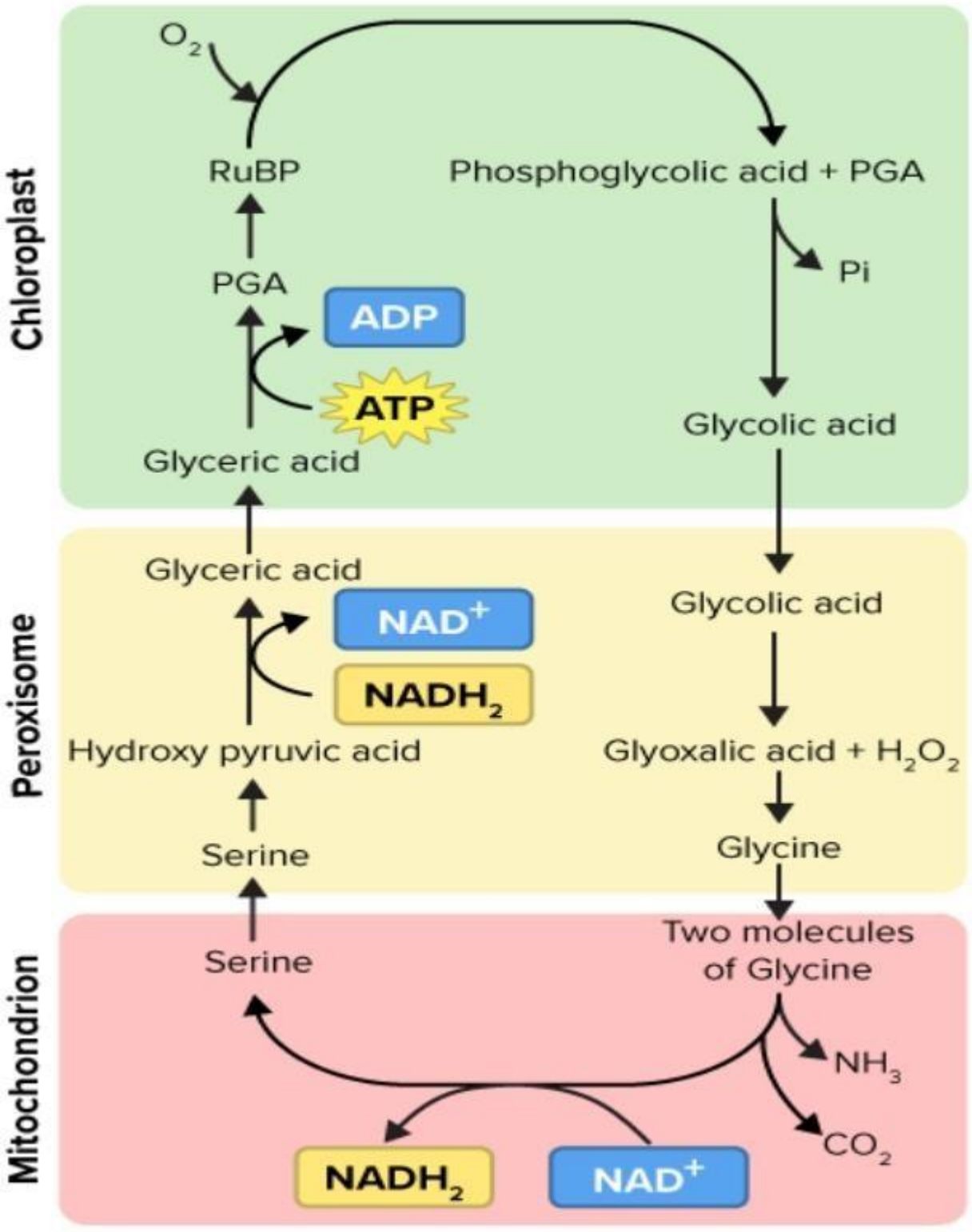

Figure 40: Photorespiration steps by peroxisomes intervention

Photorespiration decreases the efficiency (quantum yield) of photosynthesis, by degrading part of the sugars formed. In C3 plants, the ratio of photorespiration activity (moles of O_2 consumed) to photosynthesis activity (moles of O_2 released) increases as the temperature rises.

Photorespiration depends on the CO_2/O_2 ratio. It is suppressed under high CO_2 concentration.

Photorespiration derives from an intrinsic property of rubisco that appeared during a geological period when the atmospheric oxygen tension was very low.

The role of photorespiration, however, is not only negative. It is admitted that it participates in plant photoprotection. It allows the functioning of electron transfer reactions and to avoid photo-inhibition processes when plants are subjected to intensive illumination.

In this case, the CO_2 assimilation reactions proceed at maximum speed, the electron transport chain is saturated and the excess light absorbed by the photosystems produces an overexcitation of chlorophyll molecules with the risk of producing active forms of oxygen, harmful to the chloroplast and the cell.

Photorespiration, by unlocking the chain of electron transporters and also by consuming oxygen, protects from these photoinhibition processes. It also plays an important role in the synthesis of certain amino acids.

- ✓ ***Conversion of lipids to carbohydrates in seeds***

In germinating seed cells, they are associated with lipid corpuscles from which they allow the formation of carbohydrates necessary for seedling growth. In this case, the peroxysome takes the name of glyoxysome.

13.3. Differences between peroxisomes and lysosome

The main points of difference between peroxisomes and lysosomes are:

- ✓ Lysosomes are responsible for digestion in the cell while peroxisomes are responsible for protecting the cell from metabolic hydrogen peroxide.
- ✓ Lysosomes come from a Golgi or an endoplasmic reticulum. and peroxisomes are derived from the endoplasmic reticulum and are able to replicate by themselves

- ✓ Lysosomes are involved in endocytosis, autophagy and phagocytosis. and peroxisomes are involved in lipid biosynthesis and photorespiration.
- ✓ Desgradation reactions in lysosomes do not generate energy. However, the oxidative reactions in the peroxisomes generate ATP energy.

Lysosome and peroxysome two organelles containing enzymes catalyzing various biochemical processes in the cell.

The main difference between the lysosome and the peroxysome lies in the enzymes they contain and their functions: Lysosomes contain enzymes that degrade biopolymers such as proteins, lipids, polysaccharides, and nucleic acids. Peroxisomes contain enzymes for the oxidation of organic compounds and the generation of metabolic energy.

Lysosomes and peroxisomes are structurally similar, but their size varies: Lysosomes are generally more voluminous than peroxisomes and their size varies depending on the materials absorbed by the organelle. The two organelles are surrounded by a single membrane

14. Extracellular matrix

The extracellular matrix (ECM) is a three-dimensional network of macromolecules secreted by cells, located in the extracellular space. It is essential in connective tissues, but also in all animal tissues.

It provides structural support, regulates cell behavior and facilitates the organization of tissues.

The extracellular matrix (ECM) refers to all macromolecules located outside cells, but produced by them, which provide support functions, communication and tissue organization.

It is present in all multicellular organisms, but its compositions, structures and functions vary greatly between animals and plants, due to their evolutionary, structural and functional differences.

14.1. Definitions and importance (roles)

The extracellular matrix (ECM) is a dynamic non-cellular component that surrounds the cells and tissues of multicellular organisms. It acts as a support for the cells, helping them maintain their shape and function.

Moreover, the ECM serves as a reservoir for various signaling molecules, influencing cell behavior, proliferation, differentiation, and migration.

It plays a fundamental role in:

- ✓ Mechanical support of tissues
- ✓ Cell signaling
- ✓ Embryonic development
- ✓ Wound healing
- ✓ Regulation of cell growth and differentiation

14.2. Composition of the ECM

The extracellular matrix (ECM) is formed of fibrillar proteins, glycoproteins and amorphous substances (glycosaminoglycans, water, minerals) (figure 41).

A. Fibrillar proteins

- ✓ **Collagens**: represent approximately 30% of the body's total proteins, their main role being tensile strength
- ✓ **Elastin**: ensures tissue elasticity (lungs, skin)

B. Structural Glycoproteins

- ✓ ***Fibronectin***:

Fibronectin is a widespread protein present in the extracellular matrix in a soluble form. It plays a key role in cell adhesion due to its ability to bind to various ECM components, such as polysaccharides, structural proteins like collagen, as well as integrin-type membrane receptors.

✓ ***Laminin***:

Laminin is an adhesion protein primarily located in the basal laminae. It binds to certain polysaccharides, such as hyaluronic acid, as well as to integrin-type membrane receptors.

C. Proteoglycans and GAGs

✓ ***Glycosaminoglycans (GAGs):***

These are long, negatively charged polysaccharides, such as hyaluronic acid, chondroitin sulfate, and heparan sulfate.

They are polymers made up of repeated disaccharide units, including an amino sugar. They can be sulfated (such as chondroitin sulfate, dermatan sulfate, heparan sulfate, or keratan sulfate) or non-sulfated, such as hyaluronic acid.

✓ ***Proteoglycans:***

Proteoglycans are composed of a protein core to which sulfated GAGs are attached. They form very large aggregates and have the ability to bind certain cytokines and growth factors, thus playing an important role in regulating cellular activity.

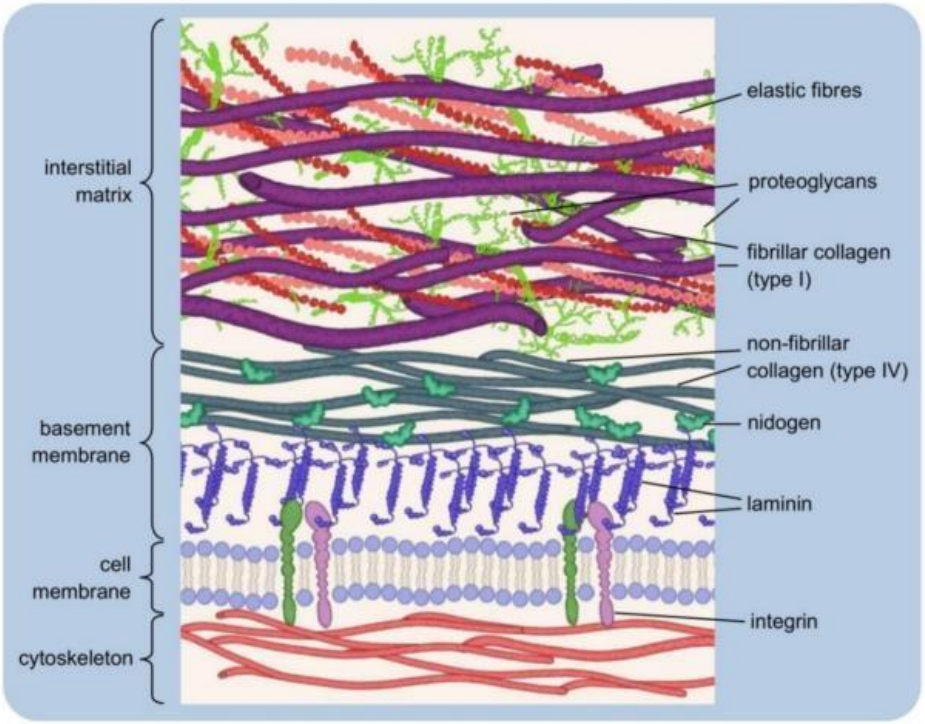

Figure 41: Simplified extracellular matrix structure.

15. Plant wall

The plant membrane, more precisely called plasma membrane, is a thin flexible and semi-permeable layer that surrounds the cytoplasm of the plant cell. It is located just below the rigid cell wall. As in all eukaryotic cells, this membrane is formed by a phospholipid bilayer into which various membrane proteins are inserted.

The wall is made up of a set of molecules synthesized by the cell and organized, outside the plasma membrane, into a plant extracellular matrix.

The extracellular matrix is called the cell wall in plants. It is very rigid, polysaccharide fibrillar structure, and present in all plant cells. It does not allow cell migration (fixed cells) and does not have major structural proteins like collagens.

Important note

The plant plasma membrane should not be confused with the plant cell wall: the latter is an external, rigid structure composed of cellulose, which provides mechanical support and additional protection to the plant cell.

15.1. Composition of the Plant Wall

The summary composition of the Plant wall is summarized in the table 5.

Table 5: Composition of the Vegetal wall

Component	**Description**	**Role**
Cellulose	Glucose polymer β(1→4)	Rigidity, structure
Hemicelluloses	Branched polysaccharides	Cellulose/matrix bond
Pectins	Acidic polysaccharides	Flexibility, porosity
Lignin (secondary wall)	Aromatic polymer	Rigidity, impermeability
Parietal proteins (extensins, expansins)	Specific proteins	Remodeling, growth
Cutin/suberin (in some cells)	Cires hydrophobes	Impermeability

- ✓ ***Cellulose:***

One of the main cell wall components. It is a linear homopolysaccharide consisting of glucose units linked by β-type glycosidic bonds (1 4).

When a partial hydrolysis of cellulose is carried out, cellobiose, a dioside formed by two β-glucose units, is obtained.

Several tens of cellulose chains assemble to form a microfibril.

These chains are stabilized together thanks to hydrogen bonds, both intra- and intermolecular, contributing to the strength of the whole.

- ✓ ***Hemicelluloses***

Hemicelluloses are complex polysaccharides, called heteropolysaccharides, because they consist of different types of sugars.

Their structure includes a linear main chain formed mainly of glucose, which can bind to cellulose by forming hydrogen bonds with the microfibrils on the surface.

They also have side chains (branches) whose sugar composition varies depending on the plant species. Hemicelluloses play an important role in cell wall cohesion and structure.

- ✓ ***Pectins:***

Pectins are polysaccharides rich in galacturonic acid, mainly found in the primary wall of plant cells and in the middle lamella (the area between two cells).

They are hydrophilic, which means that they easily retain water, and they form gels. Thanks to this property, pectins ensure the adhesion between plant cells and contribute to the flexibility and elasticity of the wall.

Their composition may vary depending on the type of plant tissue and its stage of development

- ✓ ***Lignin:***

Lignin is a complex polymer of phenolic nature, present mainly in the secondary walls of plant cells. It is particularly abundant in support and transport tissues (such as xylem).

Lignin strengthens the cell wall, makes it rigid and impermeable, which allows the conduction of water and provides mechanical resistance to the plant.

It is also a protective factor against microbial attacks. The presence of lignin usually marks the end of cell growth.

15.2. Functions

The plant wall performs several essential functions for the cell. First of all, it ensures **rigidity and mechanical support**, which allows the plant to resist gravity and stand upright. It also plays a role in determining the cell shape, by limiting the expansion of the cell according to a certain orientation.

Moreover, the wall constitutes **a protective barrier** against external aggressions, such as pathogenic microorganisms or drying out. Thanks to its porous structure, in particular at the level of the primary wall, it allows a certain regulation of exchanges between the cell and its environment.

Finally, the wall **participates in communication** between cells, notably via plasmodesmas, which are thin channels crossing the wall and connecting the cytoplasms of neighboring cells.

In summary, the plant membrane is a vital, flexible but highly organized structure that plays a fundamental role in controlling the cell's internal environment, communication and response to signals, while closely cooperating with the cell wall in plant cells.

15.3. Comparison ECM animal and plant

The plant wall and the extracellular matrix (ECM) are two structures located outside the plasma membrane, but they are specific to different kingdoms: the wall in plants, the ECM in animals.

Both provide support, protection and cellular communication functions. However, their composition is different: the plant wall is rich in cellulose, hemicelluloses, pectins and

sometimes lignin, while the ECM is mainly composed of proteins (like collagen, elastin) and complex carbohydrates (like glycosaminoglycanes) (figure 42).

Moreover, the plant wall is rigid and determines the shape of cells, while the ECM is more flexible and allows greater cellular plasticity in animals.

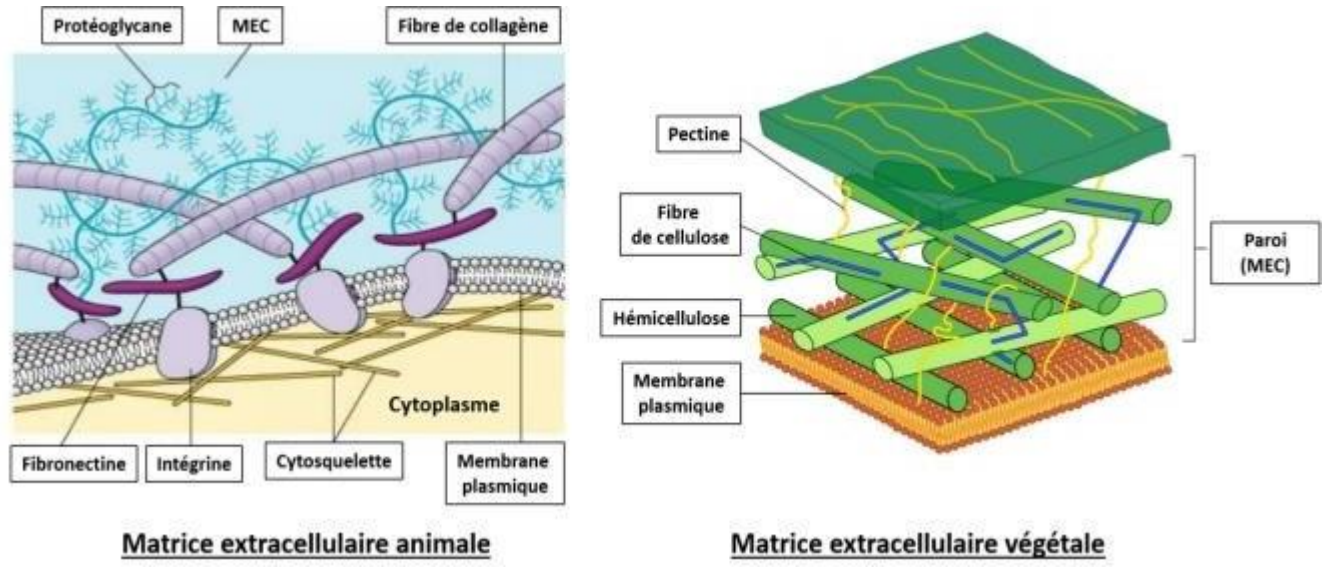

Figure 42 Comparison of animal and plant extracellular matrix

The main points of comparison between extracellular matrix and plant wall:

- ✓ ***Nature and chemical composition***:

The extracellular matrix is mainly composed of proteins (such as collagen, elastin, fibronectin) and polysaccharides (such as glycosaminoglycans), while the plant wall consists mainly of polysaccharides such as cellulose, hemicellulose, and pectin, with sometimes lignin in adult plants.

- ✓ ***Structural function***:

Both structures provide support and maintenance of the cell form. The plant wall gives a significant rigidity to the plant cell, while the ECM rather confers a controlled elasticity and flexible support to animal cells.

- ✓ ***Protection:***

The plant wall acts as a physical barrier against mechanical aggression, pathogens and osmotic pressure. For its part, the extracellular matrix participates in tissue protection, but its role is more limited in this field compared to the plant wall.

- ✓ ***Cellular communication***:

The extracellular matrix ECM plays a key role in cell signaling, interacting with membrane receptors such as integrins. It influences cell migration, proliferation and differentiation.

The plant wall, although more rigid, also allows certain forms of communication via plasmodesmas, intercellular channels crossing the wall.

- ✓ ***Origin and renewal***:

The plant wall is synthesized by the plant cell at the end of cell division (cell plate), then can be modified or strengthened (formation of secondary wall).

The ECM, on the other hand, is produced and constantly remodeled by animal cells in response to environmental signals.

- ✓ ***Dynamism***:

The ECM is very dynamic, constantly redesigned according to the needs of the tissue (e.g. healing, growth, tissue remodeling). The plant wall, although capable of modifications (cell growth, stress response), is generally more rigid and less plastic.

Thus, although the animal extracellular matrix and the plant wall fulfill analogous roles of support, protection and interaction, they clearly differ in their composition, structure and dynamism.

The table 6 summarizes the main points of comparison between extracellular matrix and plant wall

Table 6: Comparison extracellular matrix and plant wall

Criterion	**Animals**	**Plants**
Name	Extracellular matrix	Cell wall
Chemical nature	Protein and polysaccharide	Mostly polysaccharide
Main components	Collagen, fibronectin, GAGs	Cellulose, pectins, lignin
Rigidity	Flexible to semi-rigid	Very rigid (secondary wall)
Remodeling	Yes (enzymes: MMPs)	Yes but slower (parietal enzymes)
Cell migration	Possible	Impossible (fixed cells)
Cellular communication	Via receptors (integrins)	Via plasmodesmes
Presence	Connective tissues, basal lamina	All plant cells

In conclusion, although the extracellular matrix of animal cells and the wall of plant cells perform similar functions of cellular support, protection, and communication, they differ profoundly in their chemical composition, their structure, their degree of rigidity and their dynamism.

The plant wall, rigid and mainly polysaccharidic, is a permanent structure essential to the shape and survival of plant cells. On the other hand, the extracellular matrix, more flexible and rich in proteins, is a more dynamic and adaptable structure, playing a crucial role in the organization, regeneration and signaling of animal tissues.

These differences reflect the adaptation strategies specific to each kingdom in relation to their environment and ways of life.

General conclusion of the cell biology

Course of First year of university

Cell biology, as a founding discipline of the life sciences, is an essential step in the education of any student of biology, agricultural sciences, medicine, pharmacy or other fields related to life and health sciences.

It offers an initial immersion into the complexity and sophistication of the living world at the microscopic level, revealing the internal organisation, functions and interactions of cells, whether isolated or integrated into multicellular structures.

Throughout this course, we have covered the major cell categories, from prokaryotic cells (bacteria and archaea) to eukaryotic cells (animal, plant, fungal), highlighting their common characteristics and specific features.

We studied fundamental cellular structures—such as the plasma membrane, nucleus, mitochondria, endoplasmic reticulum, Golgi apparatus, lysosomes, chloroplasts, and cytoskeleton—and understood their central role in the harmonious functioning of the cell.

The cell is not simply a 'box' filled with organelles. It is a highly organised entity capable of maintaining homeostasis, carrying out regulated exchanges with its environment, producing energy, synthesising its own components, reproducing and responding to external signals.

These vital functions are performed by finely regulated biological processes, such as cell signalling, gene expression regulation, protein synthesis, and cell division mechanisms (mitosis, meiosis).

Particular attention has also been paid to the study of cell specialisation in multicellular organisms, tissue organisation, cell-cell interactions and the importance of the extracellular matrix or plant cell wall depending on the kingdom. These elements are essential for understanding how individual cells cooperate to form complex structures such as organs and systems.

Beyond descriptive aspects, modern cell biology relies on increasingly powerful observation and analysis techniques, ranging from electron microscopy to molecular approaches (immunolabelling, centrifugation, cell culture, fluorescent labelling, sequencing,

etc.), which today allow for an increasingly detailed understanding of cellular processes, with concrete applications in medicine, biotechnology, agronomy and fundamental research.

This course therefore provides an essential foundation for understanding subsequent disciplines such as molecular biology, genetics, physiology, immunology and pathology. Indeed, many diseases (cancers, genetic diseases, infections, metabolic disorders, etc.) originate from alterations in cellular functioning, making an understanding of cellular mechanisms absolutely essential for students pursuing scientific careers.

Finally, it is important to emphasise that cell biology is not a static discipline. It is constantly evolving, enriched every day by advances in research. It encourages a rigorous scientific approach: observation, hypothesis, experimentation, interpretation. It also encourages intellectual curiosity and critical thinking, fundamental qualities in any scientific endeavour.

Thus, the study of the cell, as the basic unit of life, is not only a gateway to the microscopic world, but also a conceptual and methodological foundation on which all modern biology is based. Mastering the fundamentals of cell biology therefore means equipping oneself with the means to understand biological phenomena as a whole and, ultimately, to contribute to solving the major scientific, medical and environmental challenges of our time.

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