Japan Journal of Medical - Clinical Research & Reviews

Review Article **Open Access**

Lipid Metabolism and Membrane Structure

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Abstract

Lipids are essential biomolecules that play critical roles in energy metabolism, cellular structure, and physiological regulation. This review provides a comprehensive overview of lipid metabolism and membrane structure, highlighting the biochemical and functional significance of lipids in the human body. It begins with the classification and importance of lipids, emphasizing their roles in energy storage, insulation, protection, and cell signaling. The structural and functional diversity of fatty acids, including saturated, unsaturated, essential, and non-essential types, is discussed in relation to their metabolic and physiological relevance. The review further explores triglycerides as the primary storage form of lipids, detailing their structure, classification, and metabolic pathways. Key processes in lipid metabolism, including digestion, transport via lipoproteins, and storage in adipose tissue, are discussed. Particular emphasis is placed on the degradation of fatty acids through β-oxidation, including activation, mitochondrial transport via the carnitine shuttle, and energy yield, as well as the unique metabolism of odd-chain fatty acids. Lipolysis and the metabolic fate of its products free fatty acids and glycerol are also discussed, alongside hormonal regulation. In addition, the synthesis of fatty acids is described as an important anabolic pathway occurring under energy-rich conditions. The role of lipoproteins in lipid transport and their clinical significance in metabolic disorders are highlighted. The review concludes with an in-depth detailing of the structure and function of the cell membrane, focusing on the fluid mosaic model, membrane components, and transport mechanisms. This review integrates biochemical and structural perspectives to provide a detailed understanding of lipid metabolism and membrane dynamics, with relevance to both normal physiology and disease states.
Keywords: Lipids; Fatty acids; Triglycerides; Lipid metabolism; β-oxidation; Fatty acid synthesis; Lipoproteins; Cell membrane; Fluid mosaic model; Lipolysis; Metabolic regulation; Adipose ti

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Received Date: 02 June 2026

Accepted Date: 08 June 2026

Published Date: 15 June 2026

Citation: Aluyor Adams Abraham. Lipid Metabolism and Membrane Structure. Jap J Med Clinic Res Rev. 2026; 1(1): 1- 17

1. Introduction

Lipids are a diverse group of organic compounds that are characterized by their insolubility in water and solubility in nonpolar organic solvents such as ether and chloroform (Ahmed *et al.,* 2023). In biological systems, lipids serve as a major source of energy, providing more than twice the energy per gram compared to carbohydrates and proteins (Frydrych *et al.,* 2025). They are stored primarily in the form of triglycerides in adipose tissue and can be mobilized when the body requires energy. Beyond energy storage, lipids are fundamental components of cell membranes, where phospholipids and cholesterol contribute to membrane structure, fluidity, and integrity (Torres *et al.,* 2021) This structural role is critical for maintaining the proper functioning of cells and regulating the movement of substances in and out of the cell. Lipids also play important roles in cell signaling and regulation (Santos and Preta, 2019). Certain lipids act as precursors for hormones, such as steroid hormones, and other signaling molecules like prostaglandins. Additionally, fat-soluble vitamins, including vitamins A, D, E, and K, are classified as lipids and are essential for various physiological functions, including vision, bone health, antioxidant defense, and blood clotting (Horn and Jaiswal, 2019)

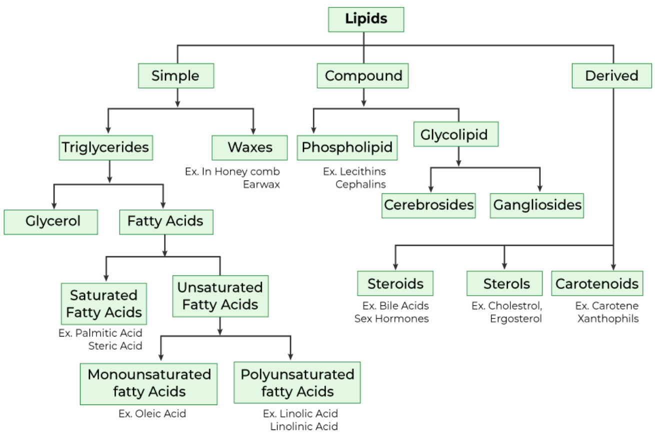

Figure 1: Classification of Lipids (Fahy *et al.,* 2011)

1.1 Importance of Lipids

1.1.1 Energy storage:

Lipids, especially triglycerides, serve as a major long-term energy reserve and provide more than twice the energy per gram compared to carbohydrates and proteins (Eliza, 2023).

1.1.2 Structural role:

They are key components of cell membranes, where phospholipids and cholesterol help maintain membrane integrity, fluidity, and selective permeability (Tirnakli, 2024)

1.1.3 Insulation:

Lipids help regulate body temperature by providing thermal insulation, particularly through adipose tissue (Gregory, 1989; Riley *et al.,* 2024).

1.1.4 Protection of organs:

Fat deposits cushion and protect vital organs such as the kidneys and heart from mechanical injury (Rosen and Spiegelman, 2014)

1.1.5 Cell signaling and hormones:

Many lipids act as signaling molecules or serve as precursors for hormones, including steroid hormones that regulate metabolism, growth, and reproduction (Sunshine and Iruela-Arispe, 2017)

1.1.6 Transport and absorption of vitamins:

Lipids aid in the absorption and transport of fat-soluble vitamins (A, D, E, and K), which are essential for various physiological functions (Andrès *et al.,* 2024).

1.1.7 Source of essential fatty acids:

Lipids provide essential fatty acids that the body cannot synthesize but are required for normal growth and development (Aldred *et al.,* 2019).

2. Fatty Acids

Fatty acids are fundamental components of many lipids and serve as important sources of energy in the body. They are organic molecules made up of long hydrocarbon chains with a terminal carboxyl group, which gives them their acidic properties (de-Carvalho and Caramujo, 2018). Fatty acids vary in length and in the number of double bonds present in their structure, leading to their classification as saturated or unsaturated (Lichtenstein, 2023).

Fatty acids are mainly found as part of triglycerides and phospholipids. They play key roles in energy storage, membrane structure, and cellular function. When required, fatty acids can be broken down through metabolic processes to release energy for cellular activities. Their structural diversity also contributes to the fluidity and functionality of cell membranes (Xu *et al.,* 2026)

2.1 Types of Fatty Acids (White, 2009; Belury *et al.,* 2023)

2.1.1 Saturated fatty acids:

These contain no double bonds between carbon atoms. They are usually solid at room temperature and are commonly found in animal fats such as butter.

2.1.2 Unsaturated fatty acids:

These have one or more double bonds in their structure and are generally liquid at room temperature. They are further divided into:

2.1.2.1 Monounsaturated fatty acids (MUFA):

Contain one double bond (e.g., oleic acid found in olive oil).

2.1.2.2 Polyunsaturated fatty acids (PUFA):

Contain two or more double bonds (e.g., linoleic acid and alpha-linolenic acid) (Gutierres *et al.,* 2025)

2.1.3 Essential fatty acids:

These are fatty acids that the body cannot synthesize and must be obtained from the diet, such as omega-3 and omega-6 fatty acids (Di Pasquale, 2009)

2.1.4 Non-essential fatty acids:

These can be synthesized by the body and therefore do not need to be obtained from the diet (Alfin-Slater *et al.,* 1965).

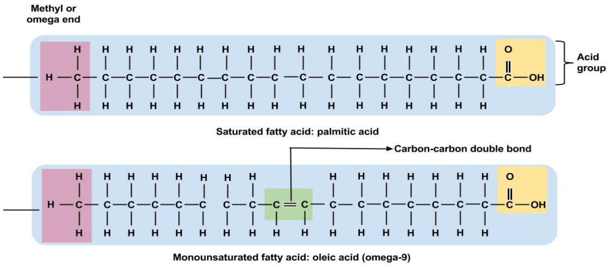

Figure 2a: Types of Fatty acid

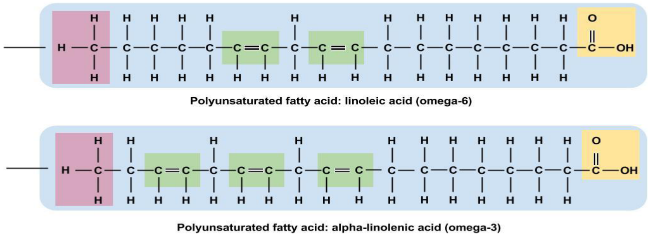

Figure 2b: Types of Fatty acid

3. Triglycerides (Triacylglycerols)

Triglycerides, also known as triacylglycerols, are the most abundant form of lipids in the human body and serve as the primary storage form of energy. They are composed of one glycerol molecule bonded to three fatty acid chains through ester linkages (Borén *et al.,* 2021). This structure allows triglycerides to store large amounts of energy in a compact and efficient form, making them essential for meeting the body's energy demands during periods of fasting or increased activity.

In the body, triglycerides are mainly stored in adipose tissue, where they act as a long-term energy reserve (Shihab *et al.,* 2024). When energy is needed, they are broken down into free fatty acids and glycerol through a process known as lipolysis. The released fatty acids can then be oxidized to produce energy, while glycerol can enter metabolic pathways such as glycolysis or gluconeogenesis.

Beyond energy storage, triglycerides also contribute to insulation and protection, helping to maintain body temperature and cushion vital organs. They are obtained from the diet, particularly from fats and oils, and can also be synthesized in the liver from excess carbohydrates and proteins (Laufs *et al.,* 2020; Hinou, 2023).

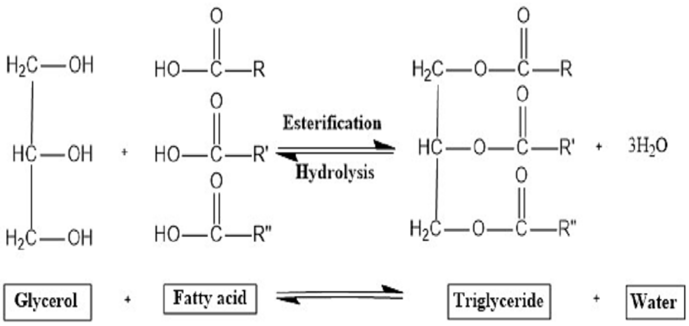

Figure 3a: Esterification and Hydrolysis of Triglycerides

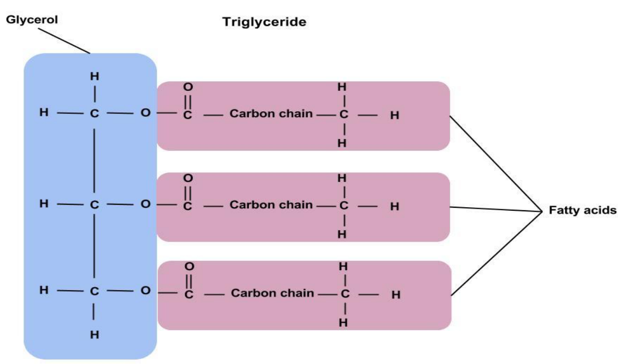

Figure 3b: Triglycerides

3.1 Types of Triglycerides

Triglycerides can be classified into simple and mixed types based on the nature of the fatty acids attached to the glycerol backbone (Bazarbashi and Miller, 2022).

3.1.1 Simple triglycerides

Simple triglycerides are those in which all three fatty acid molecules esterified to glycerol are identical. This means the triglyceride contains only one type of fatty acid repeated three times. Examples include tripalmitin, which contains three molecules of palmitic acid, and tristearin, which contains three molecules of stearic acid. These triglycerides are chemically uniform and are commonly associated with saturated fats, which tend to be solid at room temperature.

3.1.2 Mixed triglycerides

Mixed triglycerides are those in which two or three different fatty acids are attached to the glycerol molecule. In this case, the fatty acid chains may vary in length and degree of saturation, leading to a wide diversity of structures. Mixed triglycerides are the most abundant form found in natural fats and oils, occurring in both plant and animal sources. Their varied composition contributes to differences in physical properties such as melting point and fluidity.

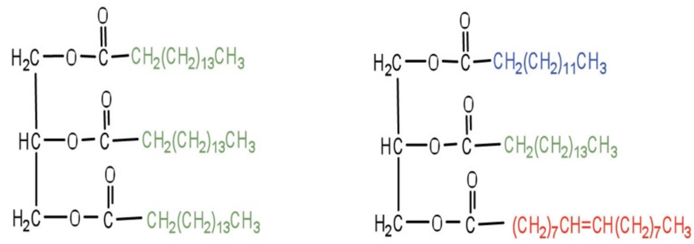

Figure 3c: Simple (Tristearin) and Mixed Triglycerides

4. Metabolism of Lipids

Lipid metabolism refers to the processes involved in the digestion, absorption, transport, synthesis, and breakdown of lipids in the body. These processes ensure that lipids are efficiently used for energy production, storage, and other vital biological functions (Chandel, 2021).

4.1 Digestion of Lipids

Dietary lipids, mainly triglycerides, are digested in the small intestine. Bile salts released from the gallbladder emulsify large fat droplets into smaller ones, increasing the surface area for enzyme action. Pancreatic lipase then breaks triglycerides into free fatty acids and monoglycerides. These products are absorbed into the intestinal cells, where they are reassembled into triglycerides and packaged into chylomicrons for transport through the lymphatic system into the bloodstream (Bakala *et al.,* 2021).

4.2 Transport of Lipids

Because lipids are insoluble in water, they are transported in the blood as lipoproteins. Chylomicrons carry dietary lipids from the intestine to tissues, while very low-density lipoproteins (VLDL) transport lipids synthesized in the liver. Low-density lipoproteins (LDL) deliver cholesterol to cells, whereas high-density lipoproteins (HDL) help remove excess cholesterol from tissues and return it to the liver (Pifferi *et al.,* 2021).

4.3 Storage of Lipids

Excess lipids are stored in adipose tissue in the form of triglycerides. This storage serves as a long-term energy reserve that can be mobilized when energy intake is low or energy demand is high (França *et al.,* 2018).

5. Degradation of Fatty Acids

When energy is required, triglycerides are broken down into fatty acids and glycerol by enzymes such as hormone-sensitive lipase (found in adipose tissue). This process is stimulated by hormones like glucagon and epinephrine and inhibited by insulin (Althaher, 2022; Talley and Mohiuddin, 2023).

5.1 β-Oxidation of Fatty Acids

It is called beta-oxidation because oxidation occurs at the β-carbon of the fatty acid. Fatty acids released during lipolysis are transported into the mitochondria, where they undergo β-oxidation. This process breaks down fatty acids into acetyl-CoA units, which enter the citric acid cycle to produce ATP. Inside the mitochondrial matrix, fatty acyl-CoA undergoes repeated cycles called β-oxidation. Each cycle shortens the fatty acid by 2 carbon atoms, producing: Acetyl-CoA, NADH and $FADH_2$ (Ghisla, 2004).

5.2 Activation of Fatty Acids in the Cytoplasm (Before β-Oxidation)

Before fatty acids can be broken down to produce energy through β-oxidation, they must first be activated in the cytoplasm (specifically on the outer mitochondrial membrane). This activation converts free fatty acids into a more reactive form known as fatty acyl-CoA.

Fatty acid + CoA + ATP → Fatty acyl-CoA + AMP + PPi

5.3 Transport of Long-Chain Fatty Acids via the Carnitine System (Longo *et al.,* 2016)

5.3.1 Long-chain fatty acyl-CoA cannot cross the inner mitochondrial membrane directly, so it uses the carnitine transport system

5.3.2 CPT-1 (Carnitine Palmitoyltransferase I) converts fatty acyl-CoA into acylcarnitine on the outer mitochondrial membrane.

5.3.3 CACT (Carnitine–Acylcarnitine Translocase) transports acylcarnitine into the mitochondrial matrix.

5.3.4 CPT-2 (Carnitine Palmitoyltransferase II) converts acylcarnitine back into fatty acyl-CoA inside the mitochondrion.

5.4 Reason for the Carnitine Shuttle

The carnitine shuttle is required because long-chain fatty acids cannot directly cross the inner mitochondrial membrane, where β-oxidation takes place. While fatty acids can be activated to fatty acyl-CoA in the cytoplasm, the inner mitochondrial membrane is highly selective and impermeable to CoA-bound fatty acids.

To overcome this barrier, the carnitine shuttle serves as a transport system that moves long-chain fatty acids into the mitochondrial matrix for energy production. In this process, the fatty acyl group is temporarily transferred from CoA to carnitine to form fatty acyl-carnitine, which can cross the membrane. Once inside the mitochondria, the fatty acid is transferred back to CoA and can then undergo β-oxidation.

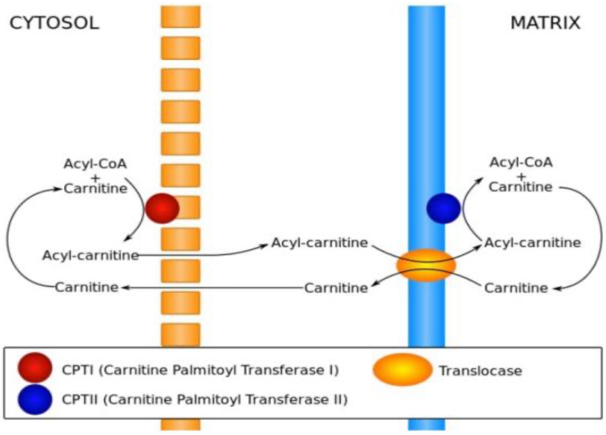

Figure 4: Carnitine shuttle

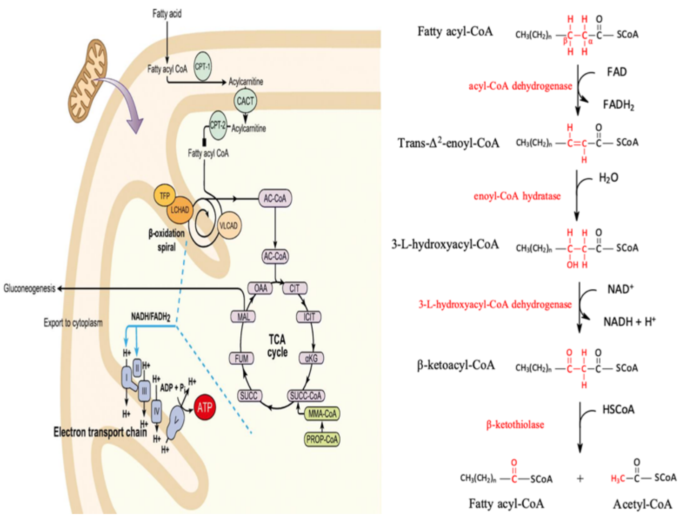

Figure 5: Overview of the β-Oxidation Pathway

5.5 Figure 5 Abbreviations

CPT-1 = Carnitine Palmitoyltransferase I; **CACT** = Carnitine–Acylcarnitine Translocase; **CPT-2** = Carnitine Palmitoyltransferase II; **TFP** = Trifunctional Protein (mitochondrial enzyme complex); **LCHAD** = Long-Chain 3-Hydroxyacyl-CoA Dehydrogenase; **VLCAD** = Very Long-Chain Acyl-CoA Dehydrogenase; **MMA-CoA** = Methylmalonyl-CoA; **PROP-CoA** = Propionyl-CoA; **β-oxidation spiral** = Repeated cycle of fatty acid breakdown in mitochondria.

5.6 Sequential Reactions in the β-Oxidation of Fatty Acids

The process in which fatty acids are degraded within the mitochondria to generate energy involves the sequential removal of two-carbon units in the form of acetyl-CoA during each cycle.

5.6.1 Oxidation by Acyl-CoA Dehydrogenase

Two hydrogen atoms are removed from Acyl-CoA and a double bond forms between: α-carbon (C2) and β-carbon (C3)

5.6.2 Hydration by Enoyl-CoA Hydratase

Water is added across the double bond and OH group attaches to the β-carbon.

5.6.3 Oxidation by 3-Hydroxyacyl-CoA Dehydrogenase

The hydroxyl group (OH) is oxidized into a keto group (=O).

5.6.4 Cleavage by β-Ketoacyl-CoA Thiolase

The bond between α and β carbons is broken, one molecule of Acetyl-CoA is released and the fatty acid becomes: 2 carbons shorter. The cycle repeats until the entire fatty acid becomes Acetyl-CoA molecules.

5.7 Example Using Palmitic Acid (16 Carbons)

Palmitic acid, which contains 16 carbon atoms, undergoes seven cycles of beta-oxidation during its complete degradation in the mitochondria. Through this process, the fatty acid molecule is progressively shortened by the removal of two-carbon units in the form of acetyl-CoA. Complete oxidation of one molecule of palmitic acid produces eight (8) molecules of acetyl-CoA, seven (7) molecules of NADH, and seven (7) molecules of $FADH_2$ (Houten and Wanders, 2010)

Palmitic Acid (16C) → 8Acetyl-CoA + 7NADH + 7FADH2

5.7.1 ATP Yield from Palmitic Acid (Jain *et al.,* 2021)

The NADH and $FADH_2$ generated during β-oxidation donate electrons to the electron transport chain for ATP production, while the acetyl-CoA molecules enter the tricarboxylic acid (TCA) cycle to produce additional ATP. Altogether, the complete oxidation of one molecule of palmitic acid yields approximately 106 molecules of ATP. This high ATP yield demonstrates why fats are considered a more concentrated and efficient source of energy compared with carbohydrates.

5.8 Special Pathway: Oxidation of Odd-Chain Fatty Acids (Jenkins *et al.,* 2015).

Unlike even-chain fatty acids, which are completely broken down into acetyl-CoA units, odd-chain fatty acids undergo β-oxidation until the final three-carbon fragment, known as propionyl-CoA (Prop-CoA), is produced. This propionyl-CoA does not directly enter the usual β-oxidation pathway. Instead, it is converted through a specialized sequence of reactions into a TCA cycle intermediate. First, propionyl-CoA is carboxylated to form methylmalonyl-CoA (MMA-CoA). This compound is then rearranged to produce succinyl-CoA (Succ-CoA), which can enter the tricarboxylic acid (TCA) cycle.

Because succinyl-CoA is a TCA cycle intermediate that can be converted into oxaloacetate, odd-chain fatty acids have a unique metabolic advantage: they can contribute not only to energy production but also to gluconeogenesis, leading to the formation of glucose. This distinguishes them from even-chain fatty acids, which cannot be used to synthesize glucose.

5.9 Summary of the β-Oxidation of Fatty Acids

i. Activated in the cytoplasm
ii. Transported into mitochondria via carnitine shuttle
iii. Broken down by β-oxidation into acetyl-CoA
iv. Acetyl-CoA enters TCA cycle
v. NADH/$FADH_2$ feed into ETC
vi. ATP is produced as final energy output

6. Fatty Acid Synthesis (Beld *et al.,* 2015)

Fatty acid synthesis is an anabolic (biosynthetic) process by which the body converts excess dietary nutrients, particularly carbohydrates, into fatty acids for long-term energy storage. This pathway occurs mainly in the cytoplasm of liver cells, adipose tissue, and lactating mammary glands, especially during the well-fed state when energy intake exceeds immediate needs.

The process begins with acetyl-CoA, which is primarily generated in the mitochondria from glucose metabolism. Since acetyl-CoA cannot cross the mitochondrial membrane directly, it is first converted to citrate, transported into the cytoplasm, and then reconverted back to acetyl-CoA. This cytosolic acetyl-CoA serves as the starting material for fatty acid synthesis. The first and most important regulatory step is the conversion of acetyl-CoA to malonyl-CoA, catalyzed by the enzyme acetyl-CoA carboxylase (ACC). This step requires ATP and biotin and represents the committed step of the pathway. Malonyl-CoA then provides two-carbon units that are repeatedly added to a growing fatty acid chain (Kalish *et al.*, 2015).

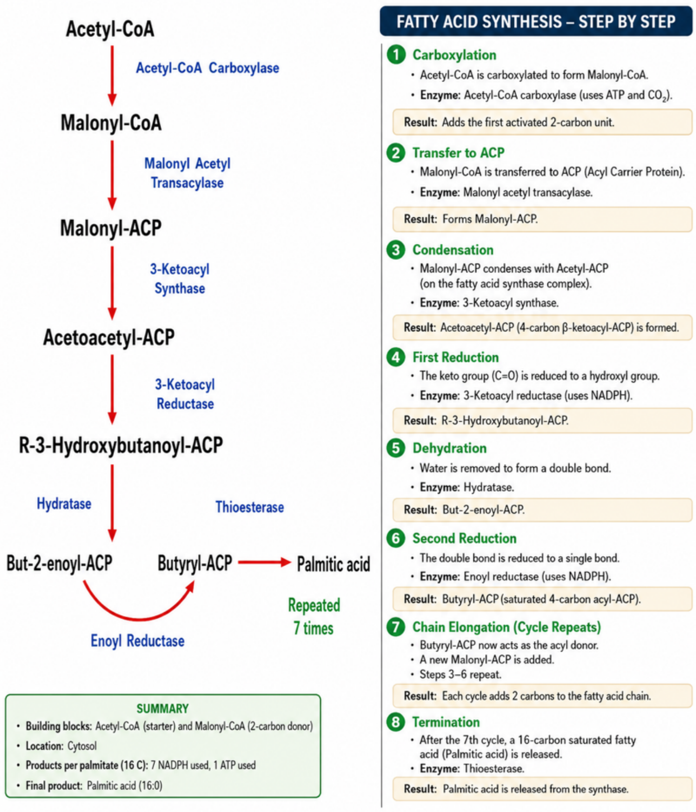

Figure 6: Fatty Acid Synthesis

7. Degradation of Triglycerides (Lipolysis)

Triglycerides are the major storage form of fat in the body. They are stored mainly in adipose tissue and serve as an important source of energy during fasting, starvation, prolonged exercise, and stress conditions. Triglyceride degradation is the biochemical process through which triglycerides are broken down into glycerol and free fatty acids. This process is known as lipolysis. The released fatty acids are used for ATP production through beta-oxidation as stated above 5.1, while glycerol can be used for glucose synthesis in the liver (Edwards and Mohiuddin, 2023)

7.1 Steps in Triglyceride Degradation (Hita *et al.*, 1996)

Triglyceride degradation occurs in three major hydrolytic steps.

7.1.1 Breakdown of Triglyceride to Diglyceride

Reaction: Triglyceride + H_2O → Diglyceride + Fatty Acid

Enzyme: Adipose Triglyceride Lipase (ATGL)

7.1.2 Breakdown of Diglyceride to Monoglyceride

Reaction: Diglyceride + H_2O → Monoglyceride + Fatty Acid

Enzyme: Hormone-Sensitive Lipase (HSL)

7.1.3 Breakdown of Monoglyceride to Glycerol

Reaction: Monoglyceride + H_2O → Glycerol + Fatty Acid

Enzyme: Monoglyceride Lipase

7.2 Fate of Free Fatty Acids (Steinberg, 1964)

The free fatty acids released during lipolysis bind to albumin in the bloodstream for transportation to various tissues of the body, particularly the liver, skeletal muscle, and heart. After entering these cells, the fatty acids are transported into the mitochondria where they undergo beta-oxidation (refer to 5.1). During this process, the fatty acids are gradually broken down to produce acetyl-CoA, NADH, and $FADH_2$. The acetyl-CoA enters the tricarboxylic acid (TCA) cycle, while NADH and $FADH_2$ donate electrons to the electron transport chain, leading to the generation of ATP, which serves as the major energy currency of the cell.

7.3 Fate of Glycerol (Melkonian *et al.*, 2026)

Glycerol is one of the end products formed during the degradation of triglycerides (lipolysis). Unlike fatty acids, which are mainly used for energy production in many tissues, glycerol is a water-soluble molecule that is transported through the bloodstream to the liver, where its metabolism primarily occurs. In the liver, glycerol serves as an important metabolic intermediate and can be utilized in multiple pathways depending on the body's energy needs. It is first phosphorylated to glycerol-3-phosphate by the enzyme glycerol kinase, and then oxidized to dihydroxyacetone phosphate (DHAP), an intermediate of both glycolysis and gluconeogenesis.

Through this conversion, glycerol can:

i. Be used for energy production via glycolysis
ii. Contribute to glucose synthesis during fasting (gluconeogenesis)
iii. Participate in the resynthesis of triglycerides when energy is abundant

7.4 Regulation of Lipolysis (Duncan *et al.,* 2007)

The major regulatory enzyme involved in lipolysis is hormone-sensitive lipase. This enzyme catalyzes the hydrolysis of stored triglycerides, leading to the release of fatty acids and glycerol into the bloodstream. Lipolysis is hormonally regulated. It is stimulated by glucagon and epinephrine, especially during conditions of low blood glucose or increased energy demand. These hormones activate hormone-sensitive lipase through a cAMP-dependent pathway, thereby increasing fat breakdown (Saltiel, 2000). In contrast, insulin inhibits lipolysis by suppressing the activity of hormone-sensitive lipase and promoting fat storage. The products formed during lipolysis have important metabolic functions. The released fatty acids are transported to tissues such as the liver and muscles, where they undergo beta-oxidation to generate acetyl-CoA and ATP (5.1). The glycerol produced is transported mainly to the liver, where it can enter glycolysis for energy production or gluconeogenesis for glucose synthesis (7.3).

8. Lipoproteins (Feingold, 2024)

Lipoproteins are complex particles made up of lipids and proteins that function primarily in the transport of lipids through the bloodstream. Since lipids such as cholesterol, triglycerides, and phospholipids are insoluble in water, they cannot circulate freely in blood plasma. Lipoproteins therefore serve as transport vehicles that carry these hydrophobic substances from one part of the body to another (Zhyvotovska *et al.,* 2019).

Lipoproteins consist of a core containing nonpolar lipids, mainly triglycerides and cholesterol esters, surrounded by a surface layer of phospholipids, free cholesterol, and specialized proteins known as apolipoproteins. The apolipoproteins help stabilize the lipoprotein structure, act as enzyme cofactors, and serve as recognition signals for cellular receptors.

Lipoproteins are synthesized mainly in the liver and intestine and play essential roles in lipid metabolism, energy distribution, hormone synthesis, and cell membrane formation. They transport dietary lipids absorbed from the intestine to tissues and also redistribute endogenous lipids synthesized in the liver to other organs of the body (Shepherd, 1994).

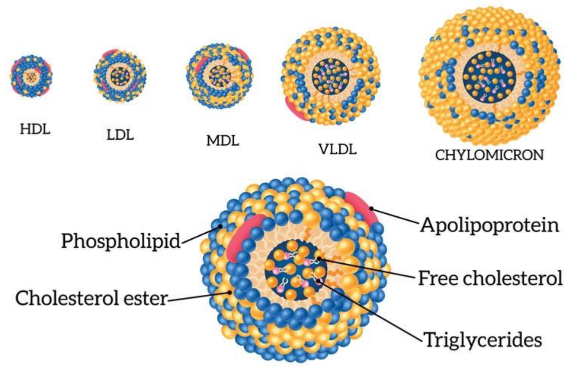

Figure 7: Types of Lipoprotein

8.1 Classification of Lipoproteins

Lipoproteins are classified according to their density, size, and composition into five major classes:

8.1.1 Chylomicrons: Transport dietary lipids from the intestine to tissues (Julve *et al.,* 2016).

8.1.2 Very low-density lipoproteins (VLDL): Transport triglycerides synthesized in the liver to tissues (Juarez, 2022).

8.1.3 Intermediate-density lipoproteins (IDL): Formed from VLDL after triglyceride removal; serves as an intermediate in the conversion of VLDL to LDL (Narang and Al-Horani, 2026).

8.1.4 Low-density lipoproteins (LDL): Delivers cholesterol to peripheral tissues ("bad cholesterol") (Venugopal *et al.,* 2026).

8.1.5 High-density lipoproteins (HDL): Removes excess cholesterol from tissues and transports it to the liver ("good cholesterol") (Bailey and Mohiuddin, 2012).

Abnormalities in lipoprotein metabolism can lead to various metabolic and cardiovascular diseases, including hyperlipidemia, atherosclerosis, coronary artery disease, and stroke (Bayly, 2014; Das and Ingole, 2023; Albitar *et al.,* 2024; Pappan *et al.,* 2026).

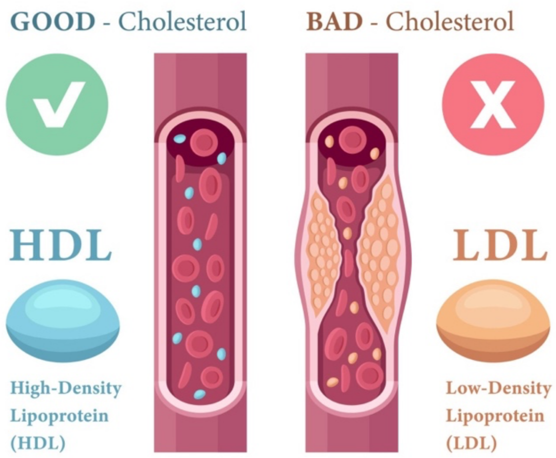

Figure 8: Good Cholesterol (HDL) vs Bad Cholesterol (LDL)

9. Structure of Cell Membrane (Cooper, 2000)

The cell membrane, also known as the plasma membrane, is a thin, flexible, and selectively permeable boundary that surrounds the cell and separates the internal environment of the cell from the external environment. It plays a vital role in maintaining the integrity, shape, and survival of the cell by regulating the movement of substances into and out of the cell Zhukov and Popov, 2023).

9.1 The Fluid Mosaic Model (Singer and Nicolson, 1972)

The Fluid Mosaic Model describes the structure of the cell membrane as a dynamic and flexible arrangement of molecules rather than a rigid structure. It was proposed by Singer and Nicolson in 1972. According to this model, the cell membrane is composed mainly of a phospholipid bilayer in which proteins are either embedded within the bilayer or attached to its surface. This arrangement creates a "mosaic" appearance because of the irregular distribution of different proteins within the lipid matrix. The membrane is described as "fluid" because both lipids and proteins are capable of lateral movement within the bilayer. This fluidity allows the membrane to remain flexible, self-sealing, and able to adapt to changes in the cell's environment. Cholesterol molecules within the membrane help regulate this fluidity by preventing it from becoming too rigid or too fluid under varying temperature conditions.

The "mosaic" aspect refers to the diverse proteins scattered throughout the lipid bilayer. These include integral proteins, which span the membrane, and peripheral proteins, which are loosely attached to its surface. These proteins perform essential functions such as transport, signaling, enzymatic activity, and structural support. Carbohydrates are also present on the outer surface of the membrane, attached to proteins and lipids, where they play roles in cell recognition and communication.

Cell Membrane = Phospholipid Bilayer + Proteins + Carbohydrates + Cholesterol

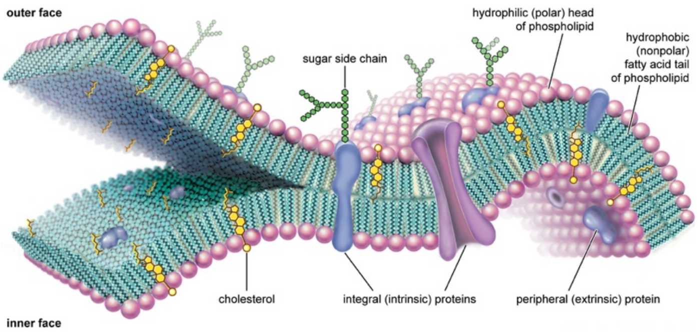

Figure 9: Structure of the Cell Membrane

10. Membrane Components (Lee, 2001; Cebecauer and Holowka, 2017)

Cell membranes are mainly composed of a lipid bilayer with embedded proteins and associated carbohydrates, which together determine the structure and function of the membrane.

10.1 Phospholipid

The major structural framework is the phospholipid bilayer, formed by amphipathic phospholipids arranged with hydrophilic heads facing outward and hydrophobic tails facing inward. This arrangement provides the membrane with its basic barrier function and fluid nature (Yang *et al.,* 2018).

10.2 Cholesterol

Cholesterol is another important lipid component found within the bilayer. It helps regulate membrane fluidity and stability by preventing the membrane from becoming too rigid at low temperatures or too fluid at high temperatures (Paukner *et al.,* 2022).

10.3 Proteins

Proteins are embedded within or attached to the lipid bilayer and are classified as integral (transmembrane) or peripheral proteins. They function in transport, signal transduction, enzymatic activity, and structural support (Jelokhani-Niaraki, 2022).

10.4 Carbohydrates

Carbohydrates are present on the outer surface of the membrane, usually attached to proteins (glycoproteins) or lipids (glycolipids). They form the glycocalyx, which is important for cell recognition, communication, and protection (Etchison and Holland, 1974; Heickendorff and Ledet, 1983).

11. Functions of the Cell Membranes

The cell membrane, also known as the plasma membrane, performs several important functions that are essential for the survival, communication, and proper functioning of the cell (Kostow, 2022).

11.1 Selective Permeability

The cell membrane regulates the movement of substances into and out of the cell. It allows essential nutrients and molecules to enter while preventing harmful substances from passing through. This helps maintain the internal environment of the cell (Davidson, 1916; Thornton, 2025).

11.2 Structural Support and Protection

The membrane provides shape and structural integrity to the cell. It acts as a protective barrier that separates the intracellular contents from the external environment and helps prevent mechanical damage (Dawkins, 2022).

11.3 Transport of Substances

The membrane controls the transport of ions, nutrients, gases, and waste products through mechanisms such as: Diffusion, Facilitated diffusion, Active transport, Endocytosis and Exocytosis (Stillwell, 2016).

11.4 Cell Communication

Specialized receptor proteins in the membrane receive chemical signals such as hormones and neurotransmitters from other cells. This enables cells to communicate and coordinate their activities (Gatenby, 2019).

11.5 Cell Recognition

Carbohydrate molecules attached to membrane proteins and lipids (glycoproteins and glycolipids) help cells recognize one another. This function is important in immune responses, tissue formation, and blood group identification (Saier, and Stiles, 1975).

11.6 Maintenance of Homeostasis

The membrane helps maintain a stable internal environment by regulating the concentration of ions, water, and other substances within the cell (Peng and Chen, 2024).

11.7 Anchoring of Cytoskeleton

The cell membrane provides attachment points for cytoskeletal filaments, which help maintain cell shape, stability, and intracellular organization (Jaqaman and Grinstein, 2012).

11.8 Enzymatic Activity

Certain membrane proteins function as enzymes that catalyze important biochemical reactions on the membrane surface (López-Cortés *et al.,* 2021).

11.9 Formation of Membrane Potential

The membrane helps establish electrical gradients across the cell by controlling ion distribution, which is essential for nerve impulse transmission and muscle contraction (Sundelacruz *et al.,* 2009).

11.10 Cell Adhesion

The membrane allows cells to attach to neighboring cells and extracellular materials, helping in tissue formation and stability (Khalili and Ahmad, 2015).

12. Membrane Transport Mechanisms

Substances move across the cell membrane through different transport mechanisms, which include passive transport, active transport, and vesicular transport (Chen and Lui F, 2026).

12.1 Passive Transport (A)

Passive transport is the movement of substances across the membrane without the use of cellular energy. In this process, molecules move from a region of higher concentration to a region of lower concentration. Examples include simple diffusion and facilitated diffusion. Simple diffusion involves the direct movement of small nonpolar molecules across the membrane, while facilitated diffusion requires the assistance of transport proteins or channels (Tomkins *et al.,* 2021).

12.2 Active Transport (B)

Active transport is the movement of substances across the membrane against their concentration gradient, from a region of lower concentration to a region of higher concentration. This process requires energy in the form of ATP. Active transport is important for maintaining ion gradients and transporting essential substances into the cell (Allen and Nolmark, 2022)

12.3 Vesicular Transport

Vesicular transport involves the movement of large molecules or particles using membrane-bound vesicles. Endocytosis is the process by which substances are taken into the cell through the formation of vesicles from the plasma membrane, while exocytosis is the process by which substances are released from the cell when vesicles fuse with the plasma membrane (Cooper, 2000; Upadhyay, 2024)

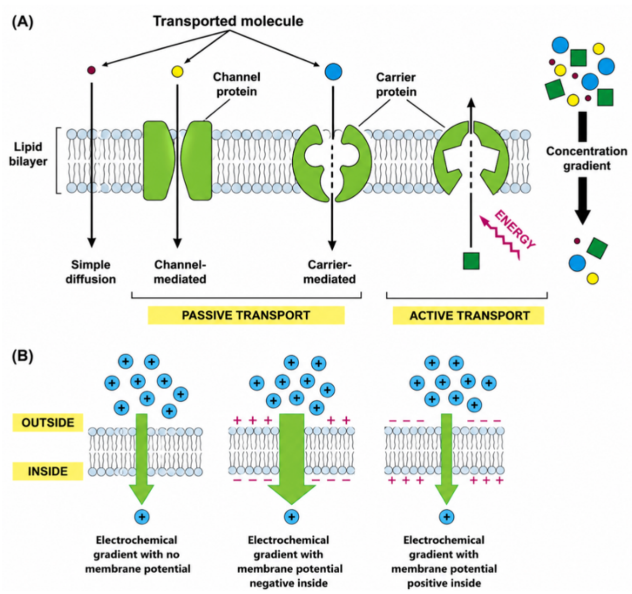

Figure 10: Membrane Transport Mechanisms

Conclusion

Lipids play indispensable roles in maintaining normal physiological functions, serving as major sources of energy, structural components of cell membranes, and key regulators of metabolic processes. This review has highlighted the complexity and integration of lipid metabolism, from the digestion and transport of dietary lipids to their storage and mobilization in the body. The breakdown of fatty acids through β-oxidation and the synthesis of new lipids under energy-rich conditions demonstrate the dynamic balance that sustains cellular and systemic energy homeostasis. Triglycerides, as the primary storage form of lipids, are central to energy metabolism, while lipoproteins ensure efficient transport of lipids within the circulatory system. The structure and function of the cell membrane underscore the importance of lipids in maintaining cellular integrity, fluidity, and communication through the fluid mosaic model. Disruptions in lipid metabolism are closely associated with various metabolic and cardiovascular diseases, emphasizing the clinical significance of understanding these biochemical pathways. Lipid metabolism and membrane dynamics are closely linked processes that are essential for life. Continued research in this field will further enhance our understanding of metabolic regulation and contribute to the development of therapeutic strategies for lipid-related disorders.

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