

A Comprehensive Review of Nutritional Supplements

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Abstract

The role of nutrition and nutraceuticals in human health and disease, covering macronutrients, micronutrients, organic acids, trace and macro minerals, vitamins, and bioactive compounds. It outlines biochemical structures, dietary sources, metabolism, physiological functions, and deficiency states of carbohydrates, proteins and amino acids, and fats. Key organic acids, choline, and taurine are described for their metabolic and digestive roles. The document evaluates dietary supplements, functional foods, nutraceuticals, designer foods, and medicinal foods, and discusses regulatory and safety challenges in supplement use. Evidence for nutraceutical applications is surveyed across cardiovascular disease, non-alcoholic fatty liver disease, cancer, obesity, osteoarthritis, diabetes, eye and skin health, asthma, neurological disorders, and gynaecological conditions, highlighting mechanisms of action, notable compounds, benefits, limitations, and safety concerns. The conclusion stresses that nutraceuticals complement but do not replace conventional therapies and calls for evidence-based use, quality assurance, regulatory oversight, and personalized integration into healthcare.

Keywords: Nutritional supplements, dietary supplements, micronutrients, macronutrients, trace minerals

INTRODUCTION

Nutritional supplements—commonly referred to as dietary supplements—represent a broad spectrum of products designed to augment one’s diet with essential nutrients or bioactive compounds not adequately obtained through conventional food. These often include vitamins, minerals, amino acids, botanicals, probiotics, and more complex substances like extracts or metabolites [1].

Although vitamins and minerals have been marketed as supplements since the early 20th century, the contemporary landscape of supplement use has expanded dramatically. Today’s consumers seek supplements not just to correct deficiencies, but to promote vitality, enhance performance, support immune function, and manage—or even prevent—chronic diseases like cardiovascular disorders, diabetes, cancer, and age-related degeneration [2].

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A global view underscores the prevalence and scale of usage. For instance, in the United States, roughly 40–50% of adults regularly consume dietary supplements, and the financial magnitude of the industry has grown exponentially—valued at billions of dollars worldwide [3] Yet, this popularity brings notable regulatory and safety challenges. In many jurisdictions, including the U.S., dietary supplements are regulated as food products, not pharmaceuticals. They are permitted to make “structure/function” claims but cannot be marketed as treatments or cures for diseases—an oversight framework established under the Dietary Supplement Health and Education Act (DSHEA) of 1994 [4].

This means manufacturers are not required to prove safety or efficacy before marketing, raising concerns about the reliability of health claims, as well as the risk of contamination, adulteration, and inconsistent quality control [5].

Given both their potential benefits and inherent risks, there is an urgent need for evidence-based guidance. This article aims to examine the scope, motivations, efficacy, and safety of nutritional supplements—highlighting their role as adjuncts to diet rather than replacements, and stressing the importance of regulation, quality assurance, and clinical research in ensuring that these products deliver real value without unintended harm [6].

NUTRITIONAL CLASSIFICATION

Nutritional supplements, including vitamins, minerals, botanicals, probiotics, and other compounds, are widely used to complement diets and support health. While historically aimed at correcting deficiencies, modern consumers also use them to boost vitality, performance, immunity, and help manage chronic diseases. Supplement use is prevalent—about 40–50% of U.S. adults take them—and the global industry is worth billions. However, regulation is limited: in the U.S., supplements are treated as foods under DSHEA (1994), allowing marketing without proof of safety or efficacy. This raises concerns about misleading claims, contamination, and quality control. Therefore, supplements should be viewed as adjuncts, not substitutes, for diet, and their safe, effective use requires stronger regulation, evidence-based guidance, and clinical research [1, 4, 6] (Figure 1).

- Macronutrients.
- Micronutrient.

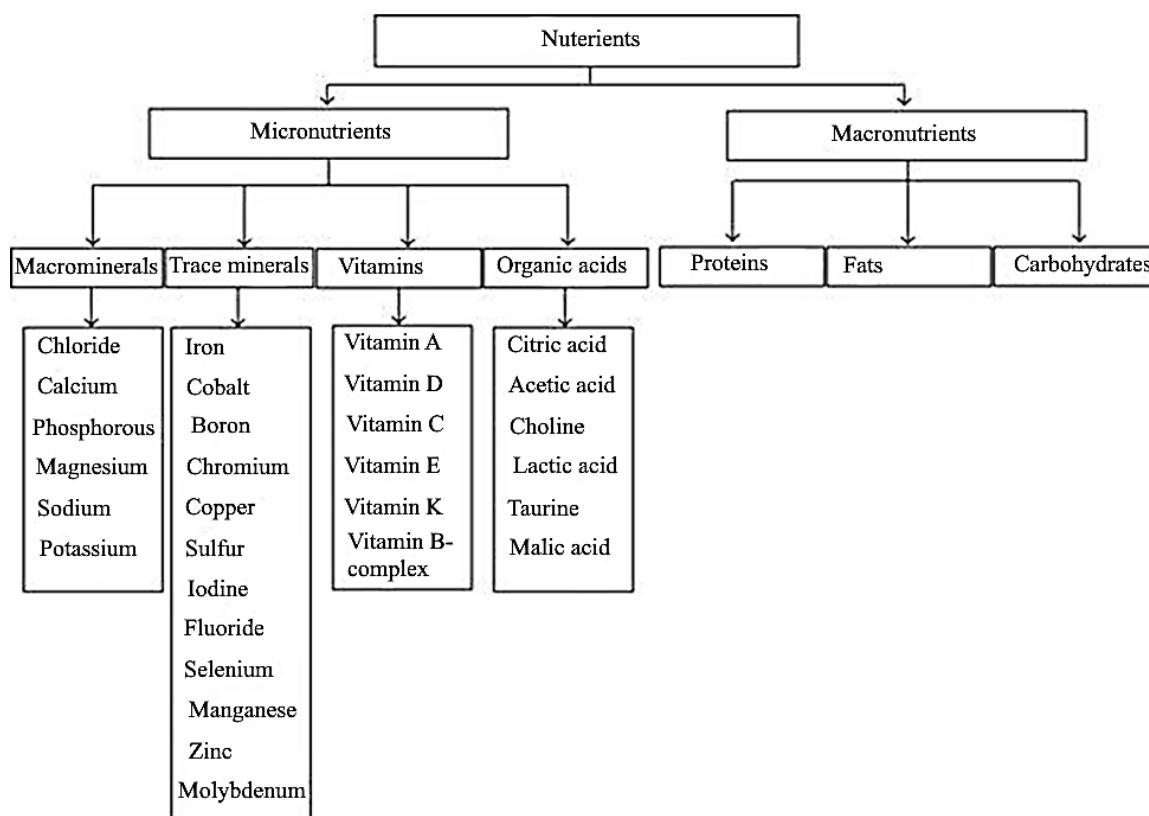


Figure 1. Nutritional classification.

Macronutrients

Macronutrients are divided into three main groups: carbohydrates, proteins, and fats. During metabolism, these nutrients are broken down into their smaller units. Carbohydrates break down into

monosaccharides, proteins into amino acids, and fats into fatty acids. Carbohydrates and fats primarily serve as sources of energy, while proteins play a vital role in building and repairing body cells and tissues. Proteins can also act as an energy source, but usually only during prolonged periods of fasting. The energy stored in macronutrients comes from their chemical bonds, which are transformed into cellular [7].

Macronutrients		Building Blocks
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Glucose	➡	Carbohydrates
Amino acid	➡	proteins
Fatty acid	➡	fats

Carbohydrates

Carbohydrates are the main source of energy that is ingested by the human body (Caffall and Mohnen 2009). Carbohydrates are polyhydroxy alcohol with potentially active carbonyl group, which may be aldehyde or keto group. Carbohydrates can be classified on the basis of carbon atom present in the carbohydrates. Carbohydrates are commonly classified as monosaccharides, disaccharides, oligosaccharides, and polysaccharides. Monosaccharides cannot be hydrolyzed further into simpler form. Disaccharides give two monosaccharides on hydrolysis. Polysaccharides may be homopolysaccharides and heteropolysaccharides (Asif et al. 2011). Plants produce carbohydrates by photosynthesis. Carbohydrates are the reservoir of energy; they also play an important role in the structure and function of the body organs and nerve cells. Carbohydrates are subdivided into several categories on the basis of the number of sugar units and how the sugar units are chemically bonded to each other. Categories include sugars, starches, and fibers. Sugars are intrinsic in fruits and milk products. Sugars also are added to foods during processing and preparation. These “added sugars” (or extrinsic sugars) sweeten the flavour of foods and beverages and improve their palatability. Sugars are also used in food preservation and for functional properties such as viscosity, texture, body, and browning capacity. They provide calories but insignificant amounts of vitamins, minerals, or other essential nutrients. The nutrition facts label provides information on total sugars per serving [8].

This broad nutrient class can sometimes confuse people because of the breadth of feedstuffs that typically provide carbohydrates to a diet. People often think of the sugars in soft drinks or the starch in breads and cereals. However, carbohydrates can also include complex sugars that are much less tasty and fibre that provides little energy value to non-fermenting animals. Everything from byproduct roughages to hays and silages, from corn starch to molasses – it is all contained within the carbohydrates nutrient class. Structural carbohydrates typically imply fibre, whereas, non-structural carbohydrates would include starches and sugars. In all species, carbohydrates provide the bulk of energy in most livestock animal diets. Foregut fermenters (such as ruminants, i.e., cows) and hindgut fermenters (such as a horse or rabbit) consume a combination of fibre and starch that have a mixed fate of microbial fermentation to volatile fatty acids (VFA) and digestion in the small intestine. The many papillae in the rumen increase surface area for VFA absorption by ruminants. Non-ruminant, non-hindgut fermenting animals, such as a pig or chicken, rely heavily on non-structural carbohydrates like starch and sugar to provide consistent energy for growth and performance [9].

Carbohydrates primarily serve as the body’s main energy source, providing 4 kcal/g. Certain cells—such as those in the brain, red and white blood cells, and kidney medulla—require glucose, though the brain can partly adapt to fat-derived fuels. While many populations (e.g., Inuit, Masai) have thrived on low- or carbohydrate-free diets, energy needs are met through gluconeogenesis using protein (amino acids) and fat (glycerol). Adults on carbohydrate-free diets require 100–150 g of protein to maintain nitrogen balance. Thus, carbohydrate requirements vary with diet composition and can approach zero after infancy, since the body can compensate through alternative energy pathways [10].

Carbohydrates – Structure & Functions

- Most abundant organic compounds in nature.
- Main energy source for the body.
- Provide 55–60% of daily energy in a normal adult diet.

Food Sources

- Grains (wheat, rice, corn).
- Legumes (beans, peas).
- Roots & tubers (potatoes, beets).
- Fruits & vegetables.

Properties

- Mostly white, solid, and dissolve in water (except some polysaccharides).

Functions

- Provide energy for body activities.

Help in the Production of

- Amino acids.
- Nucleic acids (DNA/RNA).
- Porphyrins & cholesterol.
- Glycoproteins & mucopolysaccharides.

Structural Role

- present in plant & microbial cell walls.

Chemical Structure

- *General formula:* $C_n(H_2O)_n$.
- Made of carbon, hydrogen, and oxygen.
- Monosaccharides = simplest form.

Types (Based on Units Linked by Glycosidic Bonds)

- Disaccharides → 2 monosaccharides.
- Oligosaccharides → 2–10 monosaccharides.
- Polysaccharides → >10 monosaccharides (long chains, linear or branched).

Common Monosaccharides

- Glucose.
- Fructose.

Monosaccharides (Simple Sugars)

Monosaccharides are the simplest carbohydrates, also called simple sugars. They are easily digested and quickly absorbed into the blood. If the carbonyl group is on the first carbon, they are called aldoses, and if it is on another carbon, they are ketoses. The smallest monosaccharides contain 3 carbons.

- *Examples:* Glucose, Fructose, Galactose.

Glucose (Blood Sugar)

Most important monosaccharide for life; building block of starch, glycogen, and cellulose. Preferred energy source for all organisms; the brain depends mainly on glucose. In the liver, other sugars are converted to glucose for metabolism.

- *Normal blood level:* 65–110 mg/dL.

- *Sources*: rice, wheat, corn, potatoes, honey, fruits.
- *Functions*: supplies quick energy, maintains blood sugar balance, fuel for brain and muscles.

Deficiency/Imbalance

- *Low glucose (hypoglycaemia)*: fatigue, dizziness, fainting.
- *High glucose (hyperglycaemia)*: diabetes, organ damage.

Fructose (Fruit Sugar)

Found in fruits like grapes, figs, mulberries, and in honey and molasses. Sweetest natural sugar. Combine with glucose to form sucrose (Table Sugar).

- *Sources*: fruits, honey, molasses.
- *Functions*: provides energy, used in metabolism, gives natural sweetness to foods.
- *Deficiency/Imbalance*: rarely deficient, but excess intake may cause obesity or insulin resistance.

Galactose

- Found in milk as part of lactose (glucose + galactose).
- Less sweet compared to glucose and fructose.
- Rarely found in free form.
 - *Sources*: milk and dairy products.
 - *Functions*: important for infant nutrition, part of nerve tissue and brain development.

Deficiency/Imbalance

- *Galactosemia (genetic disorder)*: liver damage, cataracts, developmental delay if untreated.

General Properties of Monosaccharides

Provide about 4 kcal per gram, same as other carbohydrates. Monosaccharides & disaccharides are sweet, while polysaccharides are not.

- Sweetness Scale (Sucrose = 100)
- Lactose → 16
- Galactose → 32
- Glucose → 74
- Sucrose → 100
- Fructose → 173 (sweetest natural sugar)
- Saccharin (artificial) → 55,000[11, 12].

Disaccharides

Disaccharides are formed when two monosaccharides join together by a glycosidic bond. They dissolve easily in water but must be broken down into their simple sugar units before absorption. The most common disaccharides are maltose, lactose, and sucrose.

Maltose (Malt Sugar)

- Formed by glucose + glucose.
- Rarely found free in nature.
- Produced during starch digestion.
 - *Sources*: germinating cereals (barley, malted grains), starch breakdown products.
 - *Functions*: provides energy (4 kcal/g), intermediate in starch digestion.
 - *Deficiency/Imbalance*: rare; deficiency of enzyme (maltase) may cause digestive discomfort.

Lactose (Milk Sugar)

- Made of glucose + galactose.
- Found naturally only in milk.

- Present in 7–8% in mother's milk and 4–5% in cow's milk.
 - *Sources*: milk and dairy products.
 - *Functions*: energy source, especially important for infants; supports calcium absorption.
 - *Deficiency/Imbalance*: lactose intolerance (lack of lactase enzyme) → bloating, gas, diarrhea after milk intake.

Sucrose (Table Sugar)

- Made of glucose + fructose.
- Obtained from sugarcane and sugar beet.
- Commonly used as household sugar.
 - *Sources*: sugarcane, sugar beet, fruits, processed foods.
 - *Functions*: quick energy source, sweetener in diet.
 - *Deficiency/Imbalance*: No natural deficiency. Excess intake → obesity, diabetes, tooth decay, metabolic disorders [13, 14].

Polysaccharides

Polysaccharides are long chains of many monosaccharide units. They may be linear or branched, and are generally insoluble in water.

Based on composition

- Homopolysaccharides → made of one type of monosaccharide (starch, glycogen, cellulose).
- Heteropolysaccharides → made of different sugars (pectin, hemicellulose).

Starch

- Main storage polysaccharide in plants.
- Broken down into glucose during digestion.
 - *Sources*: rice, wheat, maize, potatoes, beans.
 - *Functions*: major dietary energy source.
 - *Deficiency/Imbalance*: deficiency not common; excess intake may raise blood sugar in diabetics.

Glycogen

- Storage polysaccharide in animals & humans (in liver & muscles).
- Provides short-term energy (12 hrs supply).
 - *Sources*: meat, liver, muscle tissues (in small amounts).
 - *Functions*: maintains blood glucose between meals, fuel reserve during fasting/exercise.
 - *Deficiency/Imbalance*: Glycogen storage diseases (genetic) → hypoglycemia, muscle weakness.

Cellulose

- Structural polysaccharide in plants.
- Cannot be digested by humans → acts as dietary fiber.
 - *Sources*: vegetables, fruits, whole grains.
 - *Functions*: promotes bowel movement, prevents constipation, lowers cholesterol.
 - *Deficiency/Imbalance*: low intake → constipation, risk of colon disease.

Inulin & Pectin

- Inulin = plant storage polysaccharide (fructose polymer).
- Pectin = structural polysaccharide (galacturonic acid polymer).
 - *Sources*: Inulin → chicory root, onions, garlic, bananas. Pectin → apples, citrus fruits, pears.
 - *Functions*: dietary fiber; fermented in large intestine → supports good gut bacteria.
 - *Deficiency/Imbalance*: low fiber → poor digestion, higher risk of heart disease & colon cancer.

Proteins

Proteins are large molecules made up of amino acids. They are vital for growth, repair, and normal body functions.

Composition

- Contain carbon (C), hydrogen (H), oxygen (O), and nitrogen (N) (unlike carbs and fats).

Role in the Body

- Build and repair tissues.
- Maintain cell survival and function.
- About 16% of adult body weight is protein.
- Not stored in the body; constantly used and replaced.

Digestion & Metabolism

- Proteins → broken into amino acids in the digestive tract → transported to the liver → rearranged into body proteins.
- Excess amino acids cannot be stored:
- Amino group → converted to urea in liver → excreted by kidneys.
- Remaining carbon part → converted into carbohydrate or fat.

Energy Value

- 1 gram protein = 4 kcal

Functions of Proteins

- Enzymes – speed up chemical reactions (need cofactors like coenzymes or metal ions).
- Structural proteins – provide support (collagen, elastin in skin, bone, muscle, cartilage).
- Transport & storage – e.g.
 - Hemoglobin → carries oxygen
 - Myoglobin → stores oxygen in muscles
 - Transferrin → transports iron
 - Ferritin → stores iron
- Protective proteins – antibodies in immune defense.
- Hormones – many are proteins (insulin, growth hormone).
- Blood clotting – proteins help in coagulation.

Sources of Proteins

- *Animal sources:* meat, fish, eggs, milk, cheese, yogurt.
- *Plant sources:* legumes (beans, lentils, peas), soy, nuts, seeds, whole grains.

Deficiency of Proteins

- Protein-Energy Malnutrition (PEM) – occurs in low-protein diets.
- *Kwashiorkor* – protein deficiency with adequate calories; symptoms: edema, swollen belly, weak muscles, fatty liver.
- *Marasmus* – severe deficiency of both protein and calories; symptoms: extreme weight loss, muscle wasting, weakness.
- *Other Effects:* growth retardation in children, poor wound healing, weak immunity, brittle hair/nails [15, 16].

Amino Acids

Amino acids are organic compounds containing an amino group ($-NH_2$) and a carboxyl group ($-COOH$) that serve as the basic building blocks of proteins. In nutrition, amino acids are macronutrient

components required for growth, repair, energy metabolism, and synthesis of enzymes, hormones, and neurotransmitters [17].

General Role

- Proteins = macronutrient made up of amino acids.
- Provide 4 kcal/g energy but mainly serve as structural & functional molecules.

Needed for

- Muscle & tissue growth.
- Enzymes & hormones.
- Antibodies (immune system).
- Neurotransmitters.
- Repair & maintenance.

Classification of Amino Acids

- *Essential*: Histidine, Isoleucine, Leucine, Lysine, Methionine, Phenylalanine, Threonine, Tryptophan, Valine Must be supplied by diet.
- *Non-essential*: Alanine, Aspartic acid, Asparagine, Glutamic acid, Serine, etc. Body synthesizes these.
- *Conditionally essential*: Arginine, Cysteine, Glutamine, Glycine, Proline, Tyrosine Needed in stress, trauma, illness.

Sources of Amino Acids

- *Animal proteins (complete proteins)*: Meat, eggs, fish, milk → contain all essential AAs.
- *Plant proteins (incomplete proteins)*: Cereals, legumes, nuts, seeds → may lack one or more AAs (e.g., lysine in cereals, methionine in legumes).
- *Complementary proteins*: Combining plant sources (e.g., rice + beans) gives a complete profile.

Functions of Key Amino Acids

- Lysine Collagen synthesis, calcium absorption, immune support Deficiency → poor growth, anemia; Excess → GI upset.
- Leucine (BCAA) Stimulates muscle protein synthesis Excess → hypoglycemia risk.
- Isoleucine & Valine (BCAA) Energy in muscle, repair Deficiency → muscle weakness.
- Methionine Sulfur donor, precursor of cysteine & glutathione (antioxidant) Excess → homocysteine buildup (CV risk).
- Phenylalanine Precursor of tyrosine → dopamine, norepinephrine Deficiency rare; Excess harmful in PKU.
- Tryptophan Serotonin & melatonin synthesis (mood, sleep) Deficiency → insomnia, depression; Excess → EMS (toxic contamination cases).
- Glutamine Fuel for immune cells, gut integrity Deficiency in trauma/critical illness.
- Arginine Precursor of nitric oxide → vasodilation, wound healing Conditional need in growth & stress.
- Creatine (derivative) Muscle energy buffer (ATP regeneration) Supplement used by athletes.

Health Aspects

- Deficiency → Kwashiorkor, stunted growth, weak immunity, poor wound healing.
- Excess intake (via supplements) → Imbalance, metabolic stress, neurological symptoms in sensitive individuals.

Athletic Use

- *BCAA & glutamine*: muscle recovery (evidence mixed).

- *Creatine*: effective in short bursts of activity.
- *Tryptophan & arginine*: tested for sleep/mood & growth hormone but limited proof [18, 19].

Fats

Dietary fat (lipid) is one of the three energy-yielding macronutrients. It is composed mainly of triacylglycerols (plus phospholipids and sterols), provides about 9 kcal per gram (the Atwater “specific factor”), supplies the essential fatty acids linoleic (n-6) and α -linolenic (n-3), facilitates absorption and transport of fat-soluble vitamins (A, D, E, K), and is integral to cell-membrane structure and signaling [20].

Types of Fat

- Dietary fat is classified into different types based on their chemical structure and physiological role.
- Saturated Fatty Acids (SFA).
- Monounsaturated Fatty Acids (MUFA).
- Polyunsaturated Fatty Acids (PUFA).
- Trans Fatty Acids (TFA).

Saturated Fatty Acids (SFA)

These fats have no double bonds in their carbon chain, making them solid at room temperature. They are mainly found in animal products such as butter, ghee, lard, and fatty meats, as well as some tropical oils like coconut and palm oil. High intake of saturated fats has long been associated with elevated cholesterol levels [21].

Monounsaturated Fatty Acids (MUFA)

These fats contain a single double bond in their structure. Olive oil, groundnut oil, and avocados are rich sources. MUFAs are considered beneficial for cardiovascular health and are a major component of the Mediterranean diet [22].

Polyunsaturated Fatty Acids (PUFA)

These contain two or more double bonds. They include omega-6 (linoleic acid) and omega-3 (α -linolenic acid, EPA, DHA) fatty acids, which are essential because the body cannot synthesize them. PUFAs are present in vegetable oils, nuts, seeds, and fish oils. They play a vital role in cell membrane structure, brain function, and inflammatory regulation [23].

Trans Fatty Acids (TFA)

These are unsaturated fats that have been structurally altered (either naturally in ruminant fats or artificially during hydrogenation of vegetable oils). Artificial trans fats are found in margarine, bakery products, and fried foods. Research showed they increase LDL cholesterol and reduce HDL cholesterol, raising the risk of heart disease.

Sources

Dietary fats are found in both plant and animal foods. Vegetable oils such as sunflower, soybean, and corn oil are rich in polyunsaturated fatty acids, whereas olive oil and groundnut oil provide more monounsaturated fats. Animal sources like butter, ghee, lard, and fatty meats are rich in saturated fats. Marine fish oils supply long-chain omega-3 fatty acids (EPA and DHA), which play a protective role in cardiovascular and neurological health. Nuts, seeds, and dairy products are also valuable natural sources of fats [24].

Role

Fat is an essential macronutrient that provides the body with concentrated energy (9 kcal per gram), serves as a storage form of energy, and helps regulate body temperature. It supplies essential fatty acids such as linoleic and α -linolenic acids that are necessary for growth, skin health, and proper cell

membrane structure. Fats also function as carriers for the absorption of fat-soluble vitamins (A, D, E, K), which cannot be utilized effectively without dietary lipids [25].

Deficiency

A lack of dietary fat or essential fatty acids can result in various health problems. Early studies demonstrated that fat deficiency may cause scaly dermatitis, growth retardation, reduced wound healing, and impaired fertility. Deficiency in essential fatty acids also alters the structure of cell membranes, leading to poor skin condition and impaired organ function. In addition, very low-fat diets may hinder the absorption of fat-soluble vitamins, causing symptoms such as night blindness (vitamin A deficiency) and bleeding disorders (vitamin K deficiency) [26].

Micronutrients

Micronutrients are essential dietary substances that the body requires in very small quantities—typically in microgram to milligram amounts each day—but they are crucial for sustaining life and health. Unlike macronutrients such as carbohydrates, proteins, and fats that provide energy, micronutrients serve as cofactors, coenzymes, and regulators in a wide array of biochemical and physiological processes. This group includes vitamins, which are organic compounds that may be water-soluble or fat-soluble, and minerals, which are inorganic elements such as iron, iodine, zinc, and selenium. Because humans cannot synthesize these compounds in sufficient amounts, they must be obtained from the diet. Their biological importance is evident in the roles they play in metabolism, immune regulation, tissue growth, and maintenance of normal development. Deficiency of micronutrients leads to functional impairments that can manifest as growth retardation, weakened immunity, cognitive decline, and reproductive failure.

Historically, the recognition of micronutrient importance emerged with the discovery of vitamins and trace elements as “accessory food factors” in the early 20th century. Later, global health organizations emphasized their public health relevance, particularly iron, vitamin A, and iodine, as deficiencies in these nutrients were linked to increased morbidity and mortality worldwide. Modern reviews stress that while adequate intake of micronutrients is essential, excess supplementation in the absence of deficiency can also be harmful, indicating the delicate balance required in their consumption. For this reason, micronutrients are considered indispensable for maintaining metabolic integrity, yet they are needed only in trace amounts compared with macronutrients [27, 28].

Organic Acids

Organic acids are naturally occurring compounds that play an important role in nutrition, metabolism, and nutrient absorption. They include low-molecular-weight acids such as citric, lactic, malic, fumaric, and acetic acids, which are commonly found in foods and produced as intermediates of metabolic pathways. In human and animal nutrition, organic acids contribute to improving digestion and nutrient utilization. They can lower gastrointestinal pH, creating a favorable environment for nutrient absorption while also inhibiting the growth of harmful microorganisms. For example, citric acid enhances the absorption of minerals like calcium, phosphorus, and magnesium, while lactic acid aids in protein digestion and maintains intestinal health [29].

Citric Acid – Sources, Functions, and Deficiency

- *Rich Sources:* Citric acid is naturally abundant in citrus fruits such as lemons, limes, oranges, and grapefruits, with lemons and limes containing the highest levels (up to ~8% of their dry weight).
- *Functions:* It is a key intermediate in the tricarboxylic acid (TCA) cycle, essential for energy production in living organisms.
 - Acts as a chelating agent, binding minerals such as calcium and magnesium, which enhances their solubility and prevents crystal formation.
 - Supports mineral absorption and contributes to bone health by aiding in mineralization.
 - In the urinary system, citrate helps prevent kidney stone formation by binding to calcium.

- *Deficiency / Low Levels:* Although direct “citric acid deficiency” is uncommon, low citrate levels in urine (hypocitraturia) are clinically significant and associated with an increased risk of calcium kidney stones. Additionally, impaired citrate metabolism in rare metabolic disorders can affect energy production, leading to metabolic imbalance [30].

Acetic Acid – Sources, Functions, and Deficiency

- *Rich Sources:* Acetic acid is most abundantly found in vinegar, where it typically makes up 4–8% of the solution. It is also present in fermented foods (pickles, kombucha, sauerkraut, kimchi) as a natural by-product of fermentation by *Acetobacter* bacteria. Small amounts are produced in the human gut during microbial fermentation of dietary fibre.

Functions

- *Central role in metabolism:* Acetic acid is converted to acetyl-CoA, a key molecule in the tricarboxylic acid (TCA) cycle for energy production.
- Serves as a precursor for fatty acid and cholesterol synthesis.
- Has antimicrobial effects, which is why vinegar is widely used as a preservative.
- Helps regulate blood sugar levels and lipid metabolism, with some studies suggesting it improves insulin sensitivity.
 - *Deficiency / Low Levels:* Metabolic disorders that impair acetyl-CoA production (such as pyruvate dehydrogenase deficiency) can reduce acetic acid availability for energy pathways, leading to fatigue, lactic acidosis, and neurological problems. In the gut, low microbial production of acetic acid may negatively affect the balance of the microbiome and reduce protection against pathogens [31].

Choline – Sources, Functions, and Deficiency

Rich Sources

- Choline is widely available in both animal and plant foods. The richest sources include:
- Eggs (especially yolks).
- Meat (beef, chicken, pork, liver).
- Fish (salmon, cod).
- Dairy products.
- Soybeans, legumes, cruciferous vegetables, nuts, and seeds.

Functions

- *Cell structure:* Choline is a precursor for phosphatidylcholine and sphingomyelin, essential components of cell membranes.
- *Neurotransmission:* It is needed to produce acetylcholine, a neurotransmitter important for memory, muscle control, and mood regulation.
- *Methyl group donor:* Through its metabolite betaine, choline donates methyl groups for DNA methylation and gene regulation.
- *Lipid metabolism & liver function:* Choline is required for exporting fat from the liver, preventing fatty liver disease.
 - *Deficiency / Low Levels:* Choline deficiency can lead to several health issues, including Fatty liver (hepatic steatosis) and liver damage Muscle damage Neurological problems due to reduced acetylcholine synthesis in pregnant women, deficiency may impair fetal brain development and increase the risk of neural tube defects [32].

Lactic Acid – Sources, Functions, and Deficiency

Rich Sources

- Lactic acid is naturally present in.
- Fermented foods such as yogurt, kefir, sauerkraut, kimchi, sourdough bread, and pickles (produced by *Lactobacillus* and other lactic acid bacteria).

- Skeletal muscle during anaerobic glycolysis (when oxygen supply is limited).
- Small amounts are also found in some fruits and fermented beverages.

Functions

- *Energy metabolism:* Formed during glycolysis when glucose is broken down without oxygen; later converted back to glucose in the liver via the Cori cycle.
- *Gut health:* In fermented foods, lactic acid supports the growth of beneficial microbiota and preserves food.
- *Skin health:* Widely used in cosmetics as a humectant and mild exfoliant.
- *pH regulation:* Acts as a buffering agent in blood and tissues.

Deficiency / Low Levels

- True “dietary deficiency” of lactic acid does not occur, since the body produces it during glucose metabolism. However, reduced lactic acid production can indicate.
- Impaired glycolysis or muscle metabolism, leading to reduced tolerance to exercise.
- In the gut, a low level of lactic acid–producing bacteria (e.g., *Lactobacillus*) can disturb microbiota balance, reducing protection against pathogens and impairing digestion [33].

Taurine – Sources, Functions, and Deficiency:

Rich Sources

- Taurine is a sulfur-containing amino acid–like compound that is not incorporated into proteins but exists freely in tissues. It is abundant in.
- *Animal-based foods:* meat (especially beef, lamb, and dark poultry meat), fish, and seafood.
- Dairy products contain smaller amounts.

Human breast milk is also a rich source, which is important for infant development.

(Plant-based foods contain little to no taurine; vegetarians and vegans usually rely on endogenous synthesis or supplementation.)

Functions

- *Bile salt formation:* Taurine conjugates with bile acids (e.g., taurocholic acid), aiding in digestion and fat absorption.
- *Neurological function:* Acts as a neurotransmitter and neuromodulator, supporting brain development and stabilizing cell membranes.
- *Cardiovascular health:* Helps regulate calcium signaling, blood pressure, and protects against oxidative stress.
- *Antioxidant role:* Reduces damage from free radicals and supports mitochondrial function.
- *Eye and muscle health:* High concentrations are found in the retina and skeletal muscle, where it maintains function and integrity.
 - *Deficiency / Low Levels:* Taurine is generally synthesized in the human body from methionine and cysteine (with vitamin B6 as a cofactor), so deficiency is rare. However, when it occurs, it can lead to.
 - Retinal degeneration and vision problems (since taurine is crucial in the retina).
 - Impaired fat absorption due to reduced bile salt formation.
 - Neurological dysfunction and developmental delays.
 - Cardiomyopathy (observed in some animal studies when taurine is deficient).
 - Infants (especially premature) are more vulnerable because they have limited taurine synthesis capacity [34].

Malic Acid – Sources, Functions, and Deficiency

Rich Sources

Malic acid is a naturally occurring organic acid found widely in fruits and vegetables, especially in.

- Apples (the name “malic” comes from the Latin malum, meaning apple).
- Pears, cherries, plums, apricots, and peaches.
- Grapes and wine (as a fermentation intermediate).
- Some leafy vegetables and tomatoes also contain malic acid in smaller amounts.

Functions

- *Energy metabolism:* Malic acid is an important intermediate of the tricarboxylic acid (TCA) cycle, where it contributes to ATP production.
- *Detoxification:* Plays a role in removing ammonia from the body by participating in the malate–aspartate shuttle.
- *Oral health:* Used in chewing gums and toothpaste for its role in stimulating saliva production.
- *Food industry:* Added as a flavoring and preservative due to its tart taste and ability to control pH.
- *Exercise performance:* Malic acid (often combined with citrulline) is suggested to help reduce muscle fatigue by enhancing energy availability.

Deficiency / Low Levels

- There is no direct “dietary deficiency” of malic acid because it is synthesized in the human body as part of normal metabolism. However
- Impaired malate metabolism could lead to reduced efficiency in the TCA cycle, lowering energy production.
- Low availability in cells has been associated with fatigue, muscle weakness, and metabolic stress, though such cases are generally secondary to other metabolic disorders [35].

Trace Minerals

Trace minerals are nutrients that the human body needs in very small amounts, typically 100 milligrams or less per day. Although required only in such minute quantities, they are essential for a range of vital functions, including enzyme activation, metabolic reactions, growth, and maintaining overall health. Common trace minerals include copper, zinc, selenium, iodine, chromium, fluoride, manganese, and molybdenum. Importantly, a deficiency in any trace mineral can lead to health issues just as serious as those caused by a lack of major minerals. For example, severe iodine deficiency once affected around 50% of Fiji’s population in the 1990s, leading to widespread goiter—this was significantly reduced after the government mandated the use of iodized salt and promoted seafood consumption [36].

Iron – Sources, Functions, and Deficiency

Rich Sources

- Iron is found in two dietary forms:
- Heme iron (highly bioavailable, from animal sources):
- Red meat (beef, lamb).
- Poultry (especially dark meat).
- Fish and shellfish (sardines, clams, oysters).
- Non-heme iron (from plant sources, less readily absorbed):
- Legumes (lentils, beans, chickpeas).
- Leafy greens (spinach, kale).
- Fortified cereals and whole grains.
- Nuts and seeds.

Functions

- *Oxygen transport:* Iron is a key component of haemoglobin in red blood cells and myoglobin in muscles, enabling oxygen delivery throughout the body.

- *Energy metabolism:* Functions as a cofactor in enzymes of the electron transport chain, critical for ATP production.
- *DNA synthesis and cell growth:* Essential for rapidly dividing cells, including those in the immune system.
- *Neurological function:* Supports neurotransmitter synthesis and proper brain development.

Deficiency / Low Levels

- Iron deficiency is the most common nutritional deficiency worldwide. It can lead to:
- Iron-deficiency anaemia – characterized by fatigue, pallor, weakness, and shortness of breath.
- Cognitive impairment and poor concentration (especially in children).
- Compromised immunity, increasing susceptibility to infections.
- *In severe cases:* developmental delays in children and complications during pregnancy (e.g., preterm birth, low birth weight) [37].

Copper – Sources, Functions, and Deficiency

Rich Sources

- Copper is an essential trace mineral found in a variety of foods, including:
- Organ meats (especially liver)
- Shellfish (oysters, crabs, lobsters)
- Nuts and seeds (cashews, sunflower seeds, sesame seeds)
- Legumes (lentils, beans, chickpeas)
- Whole grains (wheat, quinoa, oats)
- Dark chocolate and cocoa products

Functions

- *Enzyme cofactor:* Copper is a component of many enzymes (cuproenzymes) such as cytochrome c oxidase, lysyl oxidase, superoxide dismutase, and dopamine β -hydroxylase.
- *Energy production:* Required in the electron transport chain for cellular ATP generation.
- *Connective tissue formation:* Supports cross-linking of collagen and elastin, maintaining blood vessels, skin, and bone strength.
- *Iron metabolism:* Essential for iron absorption and incorporation into haemoglobin, preventing anaemia.
- *Antioxidant defence:* Through superoxide dismutase, copper helps protect cells against oxidative damage.
- *Nervous system function:* Plays a role in neurotransmitter synthesis and myelin formation.

Deficiency / Low Levels

Copper deficiency is uncommon but can occur due to malnutrition, genetic disorders (e.g., Menkes disease), or excessive zinc intake. Effects include.

- Anaemia (like iron deficiency, due to impaired iron metabolism).
- Neutropenia (low white blood cell count, leading to infections).
- Bone abnormalities (osteoporosis, connective tissue defects).
- Neurological problems (ataxia, peripheral neuropathy, impaired development in infants).
- Hypopigmentation of skin and hair (due to reduced melanin production) [38].

Iodine – Sources, Functions, and Deficiency

Rich Sources

- Iodine is a trace element found in foods of marine origin and fortified products:
- Seafood (fish, shellfish, seaweed/kelp).
- Dairy products (milk, yogurt, cheese – due to iodine in cattle feed and sanitizing solutions).
- Iodized salt (primary dietary source in many countries).

- Eggs (especially yolk)
- Smaller amounts in grains and vegetables, depending on soil iodine content.

Functions

- *Thyroid hormone synthesis:* Iodine is essential for production of thyroxine (T4) and triiodothyronine (T3), hormones that regulate growth, development, and metabolism.
- *Brain development:* Critical during pregnancy and infancy for proper neurodevelopment.
- *Metabolism regulation:* Supports energy production, protein synthesis, and overall metabolic rate.
- *Reproductive health:* Adequate iodine supports fertility and healthy pregnancy outcomes.

Deficiency / Low Levels

- Iodine deficiency is still a global health issue, especially in areas with low soil iodine. Effects include:
 - Goiter (enlargement of the thyroid gland).
 - Hypothyroidism (fatigue, weight gain, cold intolerance, slow growth).
 - Cretinism (severe, irreversible intellectual disability and stunted growth in infants born to iodine-deficient mothers).
 - Pregnancy complications (miscarriage, stillbirth, impaired brain development in the foetus).
 - Impaired cognitive function and learning disabilities in children [39].

Selenium – Sources, Functions, and Deficiency

Rich Sources

Selenium content in foods varies depending on soil concentration, but the best dietary sources include

- Brazil nuts (one of the richest sources).
- Seafood (tuna, sardines, shrimp, oysters).
- Organ meats (liver, kidney).
- Poultry and eggs.
- Whole grains and cereals (if grown in selenium-rich soil).
- Dairy products (milk, yogurt, cheese).

Functions

- *Antioxidant defense:* Selenium is an essential component of selenoproteins such as glutathione peroxidases and thioredoxin reductases, which protect cells from oxidative stress.
- *Thyroid function:* Necessary for the activity of iodothyronine deiodinases, enzymes that convert thyroxine (T4) into the active form triiodothyronine (T3).
- *Immune system regulation:* Supports proper immune response and helps defend against infections.
- *Reproductive health:* Important for sperm motility and overall fertility.
- *Cardiovascular health:* May reduce the risk of certain heart conditions through antioxidant and anti-inflammatory roles.

Deficiency / Low Levels

Selenium deficiency is uncommon but can occur in populations with low soil selenium. Effects include.

- Keshan disease – a cardiomyopathy (heart muscle disorder) linked to selenium deficiency and viral infection.
- Kashin-Beck disease – an osteoarthropathy causing joint and bone deformities.
- Hypothyroidism – due to impaired thyroid hormone metabolism.
- Weak immune function – increasing susceptibility to infections.
- In severe cases, male infertility due to impaired sperm function [40].

Manganese – Sources, Functions, and Deficiency

Rich Sources

- Manganese is a trace mineral found mainly in plant-based foods. Good dietary sources include.
- Whole grains (brown rice, oats, wheat).
- Legumes (beans, lentils, chickpeas).
- Nuts and seeds (almonds, hazelnuts, sunflower seeds).
- Leafy green vegetables (spinach, kale).
- Tea (especially black tea, which is a notable source).
- Pineapple and blueberries.

Functions

- *Enzyme cofactor:* Manganese activates several enzymes, including manganese superoxide dismutase (MnSOD), which protects mitochondria from oxidative stress.
- *Bone development:* Essential for the synthesis of bone matrix proteins and cartilage.
- *Metabolism:* Involved in the metabolism of carbohydrates, amino acids, and cholesterol.
- *Wound healing:* Supports collagen formation and tissue repair.
- *Reproductive health and brain function:* Plays a role in neurotransmitter synthesis and regulation.

Deficiency / Low Levels

Manganese deficiency is rare but can occur due to poor dietary intake, genetic disorders, or parenteral nutrition lacking manganese. Effects include.

- Skeletal abnormalities (poor bone growth, bone deformities).
- Impaired glucose tolerance (possible contribution to diabetes-like symptoms).
- Skin rashes and poor wound healing.
- Reproductive issues (infertility in severe cases).
- Neurological symptoms (ataxia, tremors, mood changes) [41].

Zinc – Sources, Functions, and Deficiency**Rich Sources**

Zinc is widely distributed in foods, with animal-based sources providing the most bioavailable form.

- Oysters (one of the richest sources).
- Red meat (beef, lamb, pork).
- Poultry (chicken, turkey).
- Seafood (crab, lobster, sardines).
- Legumes (beans, lentils, chickpeas – though less bioavailable due to phytates).
- Nuts and seeds (pumpkin seeds, cashews, almonds).
- Whole grains and fortified cereals.
- Dairy products and eggs.

Functions

- *Enzyme activity:* Cofactor for over 300 enzymes involved in digestion, DNA/RNA synthesis, protein production, and cell division.
- *Immune function:* Supports development and activation of immune cells, helping fight infections.
- *Growth and development:* Critical for growth in children, wound healing, and reproductive health.
- *Skin health:* Important in tissue repair and used therapeutically in acne and wound healing.
- *Neurological function:* Plays a role in neurotransmission and brain health.
- *Taste and smell:* Zinc is essential for proper function of taste buds and olfactory cells.

Deficiency / Low Levels

Zinc deficiency can result from inadequate intake, malabsorption, chronic illness, or increased requirements (e.g., pregnancy). Effects include:

- Growth retardation and delayed sexual maturation in children.
- Impaired immunity → frequent infections.
- Skin lesions and poor wound healing.
- Hair loss (alopecia).
- Loss of taste and smell (hypogeusia, anosmia).
- Diarrhea and poor appetite.
- *In severe cases*: congenital defects, impaired neurodevelopment, or acrodermatitis enteropathica (a rare genetic disorder) [42].

Molybdenum – Sources, Functions, and Deficiency

Rich Sources

Molybdenum is a trace element found in both plant and animal foods, especially in legumes. Key dietary sources include.

- Legumes (lentils, beans, chickpeas, soybeans).
- Whole grains (oats, barley, buckwheat).
- Nuts and seeds (almonds, sunflower seeds).
- Leafy vegetables (spinach, kale).
- Organ meats (liver, kidney).
- Milk and dairy products.

Functions

Molybdenum functions primarily as a cofactor for several important enzymes, called molybdoenzymes, including.

- Sulphite oxidase – breaks down sulphites in foods and drugs.
- Xanthine oxidase – involved in purine metabolism and uric acid formation.
- Aldehyde oxidase – detoxifies aldehydes and certain drugs.
- Mitochondrial amidoxime reducing component (MARC) – involved in detoxification of harmful compounds.
- Through these enzymes, molybdenum contributes to:
- Detoxification of sulphites and drugs.
- Metabolism of purines, amino acids, and sulphur-containing compounds.
- Antioxidant defence and energy production.

Deficiency / Low Levels

Molybdenum deficiency is extremely rare in humans but may occur in cases of genetic defects (e.g., molybdenum cofactor deficiency) or prolonged parenteral nutrition without supplementation. Symptoms include.

- Neurological abnormalities (seizures, developmental delay, disorientation).
- Vision and hearing loss (in severe genetic deficiency).
- Increased sensitivity to sulphites (causing asthma-like symptoms).
- Mental retardation and early death (in rare inherited deficiency disorders) [43].

Chromium – Sources, Functions, and Deficiency

Rich Sources

Chromium is a trace mineral found in small amounts in a wide variety of foods. Sources include.

- Whole grains (whole wheat bread, oats, bran cereals).
- Meats (beef, chicken, turkey).
- Seafood (shellfish, mussels).
- Fruits and vegetables (broccoli, grapes, apples, green beans, potatoes).
- Nuts and spices (black pepper, nuts).
- Brewer's yeast (rich source).

Functions

Chromium plays a role in

- *Glucose metabolism:* Enhances the action of insulin, improving uptake of glucose into cells.
- *Macronutrient metabolism:* Involved in the metabolism of carbohydrates, fats, and proteins.
- *Lipid regulation:* May help maintain normal cholesterol and triglyceride levels.
- *Possible role in weight management and diabetes control:* Some studies suggest chromium improves insulin sensitivity, although evidence is mixed.

Deficiency / Low Levels

Chromium deficiency is rare, but when it occurs, especially in patients receiving long-term parenteral nutrition without supplementation, effects may include.

- Impaired glucose tolerance (symptoms similar to diabetes mellitus).
- Weight loss and muscle wasting.
- Nerve and brain abnormalities (confusion, peripheral neuropathy).
- Increased risk of metabolic syndrome.
- Elevated blood cholesterol and triglycerides [44–50].

Macrominerals

Macrominerals are essential minerals required by the human body in relatively large amounts (more than 100 mg/day). They play a crucial role in maintaining structural integrity, fluid balance, nerve transmission, muscle contraction, and metabolic functions. The primary macrominerals include Calcium, Phosphorus, Magnesium, Sodium, Potassium, Chloride, and Sulfur. Unlike trace minerals, these are needed in grams or hundreds of milligrams daily, making them vital for bone health, electrolyte balance, and overall metabolism [51].

Chloride (Cl⁻)

Sources

- Common salt (sodium chloride, NaCl → table salt).
- Seaweed, rye, tomatoes, lettuce, celery, olives.
- Processed foods (pickles, canned soups).

Functions

- Maintains fluid & electrolyte balance in the body.
- Component of gastric hydrochloric acid (HCl) → helps in digestion.
- Maintains acid–base balance (pH of blood).
- Works with sodium & potassium in nerve transmission & muscle contraction.
- Deficiency [Hypochloraemia – very rare].
- Usually due to prolonged vomiting, diarrhoea, or excessive sweating.

Symptoms

- Loss of appetite.
- Muscle weakness, cramps.
- Dehydration.
- Acid–base imbalance → metabolic alkalosis.
- In severe cases → low blood pressure, irregular heartbeat [52].

Calcium (Ca²⁺)

Sources

- Milk & milk products (curd, cheese, paneer).
- Green leafy vegetables (spinach, broccoli, kale).
- Nuts & seeds (almonds, sesame, chia).

- Fish with bones (sardines, salmon).
- Fortified foods (bread, cereals, orange juice).

Functions

- Bone & teeth formation (main structural mineral with phosphorus).
- Blood clotting (essential for coagulation cascade).
- Muscle contraction (including heart muscle).
- Nerve impulse transmission.
- Hormone & enzyme activation (second messenger role).

Deficiency

(Hypocalcaemia)

- Rickets (in children – soft, deformed bones).
- Osteomalacia & Osteoporosis (in adults – weak, brittle bones).
- Muscle cramps, spasms (tetany).
- Numbness & tingling in fingers.
- Severe cases → abnormal heart rhythm [53].

Phosphorus (P)

Sources

- Milk & milk products (curd, cheese).
- Meat, poultry, fish, eggs.
- Nuts, beans, lentils.
- Whole grains & cereals.
- Soft drinks (phosphates as additives).

Functions

- Bone & teeth formation (with calcium, forms hydroxyapatite).
- Energy metabolism (ATP, ADP → body's energy currency).
- Cell structure (phospholipids in cell membranes).
- Acid–base balance (phosphate buffer system in blood).
- DNA & RNA synthesis (nucleic acids contain phosphate groups).

Deficiency

(Hypophosphatemia – rare)

- Bone weakness, rickets/osteomalacia.
- Muscle weakness, fatigue.
- Poor growth & impaired cell function.
- Severe cases → confusion, respiratory failure, haemolytic anaemia [54].

Magnesium (Mg²⁺)

Sources

- Green leafy vegetables (spinach, kale – chlorophyll has Mg).
- Nuts & seeds (almonds, cashews, pumpkin seeds).
- Whole grains (brown rice, oats).
- Legumes (beans, lentils).
- Bananas, dark chocolate, seafood.

Functions

- Cofactor in 300+ enzymes (metabolism of carbs, proteins, fats).

- Energy production (ATP stabilization requires Mg^{2+}).
- Muscle contraction & nerve transmission.
- Bone health (works with calcium & vitamin D).
- Regulates blood pressure & heart rhythm.

Deficiency

(Hypomagnesemia)

- Muscle cramps, spasms, tremors.
- Weakness, fatigue.
- Numbness, tingling.
- Abnormal heart rhythms (arrhythmia).
- In severe cases → seizures, hypocalcaemia & hypokalaemia (because Mg regulates Ca^{2+} & K^+ balance) [55].

Sodium (Na^+)

Sources

- Table salt (NaCl).
- Processed & packaged foods (chips, canned foods, pickles).
- Bread, cheese, butter.
- Meat, seafood, eggs.
- Drinking water (sometimes contains sodium salts).

Functions

- Maintains fluid & electrolyte balance (osmotic pressure).
- Nerve impulse transmission (Na^+/K^+ pump).
- Muscle contraction (esp. heart & skeletal muscles).
- Acid–base balance (buffer system in blood).
- Helps regulate blood pressure & volume.

Deficiency

(Hyponatremia)

- Nausea, vomiting, headache.
- Muscle cramps, weakness, confusion.
- Low blood pressure, dizziness.
- Severe cases → seizures, coma, brain swelling [56].

Potassium (K^+)

Sources

- Fruits (banana, orange, apricot).
- Vegetables (spinach, potato, tomato).
- Legumes & pulses (beans, lentils).
- Milk & yogurt.
- Fish & meat.

Functions

- Maintains intracellular fluid balance (opposite to Na^+).
- Nerve impulse transmission.
- Muscle contraction (including heart).
- Helps regulate blood pressure (lowers risk of hypertension).
- Involved in carbohydrate metabolism & protein synthesis.

Deficiency

(Hypokalaemia)

- Muscle weakness, cramps.
- Fatigue, constipation.
- Heart arrhythmias (irregular heartbeat).
- Severe cases → paralysis, respiratory difficulty [57].

Vitamin

Animals require vitamins in two primary categories: water-soluble and fat-soluble vitamins. Fat soluble vitamins A, D, E, and K are required across animal species while water-soluble vitamins are often only required by non-ruminants. Ruminant microbes build their own B-vitamins and when they die, they pass downstream and are digested to provide those B vitamins to the animal. Unique to guinea pigs, vitamin C (water soluble) is also required, while for the nonruminant rabbits, coprophagy leads to the consumption of microbial-derived B-vitamins in the feces. When identifying feedstuffs for an activity, it is uncommon to have vitamins on the table. This is because vitamins are required in very small amounts and are typically mixed into a premix.

Vitamins A

Sources

- Animal → Liver, egg yolk, milk, fish oil.
- Plant → Carrot, spinach, mango, papaya, green leafy veg.

Functions

- Vision (night vision).
- Healthy skin & epithelial tissue.
- Immunity & growth.

Deficiency

- Night blindness.
- Xerophthalmia, Bitot's spots, Keratomalacia.
- Dry skin, low immunity [45].

Vitamin B Complex

Types

- B1 – Thiamine
- B2 – Riboflavin
- B3 – Niacin
- B5 – Pantothenic acid
- B6 – Pyridoxine
- B7 – Biotin
- B9 – Folic acid
- B12 – Cobalamin

Sources

- Whole grains, cereals, nuts.
- Milk, eggs, meat, liver, fish.
- Green leafy vegetables, legumes, fruits.

Functions

- Energy production (carbohydrate, protein, fat metabolism).
- Nervous system health.

- Red blood cell formation.
- DNA & RNA synthesis (especially B9, B12).
- Skin, hair & liver health.

Deficiency (by type)

- *B1 (Thiamine)*: Beri-beri, Wernicke–Korsakoff syndrome.
- *B2 (Riboflavin)*: Cheilitis (cracks at mouth corner), glossitis, dermatitis.
- *B3 (Niacin)*: Pellagra (3D's → Dermatitis, Diarrhea, Dementia).
- *B5 (Pantothenic acid)*: Rare, but fatigue, irritability, numbness.
- *B6 (Pyridoxine)*: Anemia, irritability, seizures, peripheral neuropathy.
- *B7 (Biotin)*: Dermatitis, hair loss, fatigue.
- *B9 (Folic acid)*: Megaloblastic anemia, neural tube defects in fetus.
- *B12 (Cobalamin)*: Pernicious anemia, neurological problems [46].

Vitamin C (Ascorbic Acid)

Sources

- Citrus fruits → Orange, Lemon, Sweet lime.
- Amla (Indian gooseberry).
- Guava, Strawberry, Kiwi.
- Tomatoes, Capsicum, Broccoli.
- Green leafy vegetables.

Functions

- Powerful antioxidant (protects cells).
- Helps in collagen synthesis → wound healing, skin, gums.
- Improves iron absorption (non-heme iron from plants).
- Boosts immunity against infection.
- Maintains healthy bones & teeth.

Deficiency

- Scurvy → bleeding gums, loose teeth, poor wound healing.
- Weak immunity → frequent infections.
- Fatigue, anemia (due to poor iron absorption).
- Dry skin, joint pain [47].

Vitamin D (Calciferol)

Sources

- Sunlight → Skin makes Vitamin D when exposed to UV rays.

Food Sources

- Fish liver oil, Salmon, Sardine.
- Egg yolk, Butter, Cheese.
- Fortified milk & cereal.

Functions

- Maintains calcium & phosphorus balance in blood.
- Helps in bone & teeth formation (works with parathyroid hormone).
- Important for muscle contraction & nerve transmission.
- Supports the immune system.
- Prevents rickets & Osteomalacia.

Deficiency

- *Children*: Rickets → bowed legs, delayed growth.
- *Adults*: Osteomalacia → bone pain, soft bones.
- *Elderly*: Osteoporosis → fragile bones, fractures.
- Muscle weakness, fatigue [48].

Vitamin K

Sources

Plant source (Vitamin K1 – Phylloquinone)

- Green leafy vegetables (spinach, cabbage, broccoli, kale).
- Soybean, vegetable oils.
- Animal / Bacterial source (Vitamin K2 – Menaquinone):
- Meat, liver, egg yolk, cheese.
- Intestinal bacteria synthesis.

Functions

- Essential for blood clotting (formation of clotting factors II, VII, IX, X in liver).
- Maintains bone health (helps bind calcium to bone).
- Supports vascular health (prevents calcification of arteries).

Deficiency

- Bleeding / hemorrhage (delayed blood clotting, easy bruising).
- *Newborns*: Hemorrhagic disease of the newborn.
- Osteoporosis (weak bones due to poor calcium binding) [49].

Vitamin E (Tocopherol)

Sources

- Vegetable oils (sunflower, safflower, wheat germ oil).
- Nuts & seeds (almonds, peanuts, sunflower seeds).
- Green leafy vegetables (spinach, broccoli).
- Whole grains, fortified cereals.

Functions

- Acts as a powerful antioxidant → protects cell membranes from free radical damage.
- Maintains skin & hair health.
- Supports immune function.
- Helps in red blood cell (RBC) protection → prevents hemolysis.
- May reduce risk of heart disease by preventing LDL oxidation.

Deficiency

- Rare, but may occur in premature infants or malabsorption disorders.
- Hemolytic anemia (due to fragile RBCs).
- Muscle weakness, peripheral neuropathy (nerve damage).
- Poor immunity.
- Vision problems (retinopathy in severe cases) [50] (Figure 2).

Nutritional Resources Classification

- Dietary Supplements.
- Functional Foods.
- Medicinal food.
- Designer food.

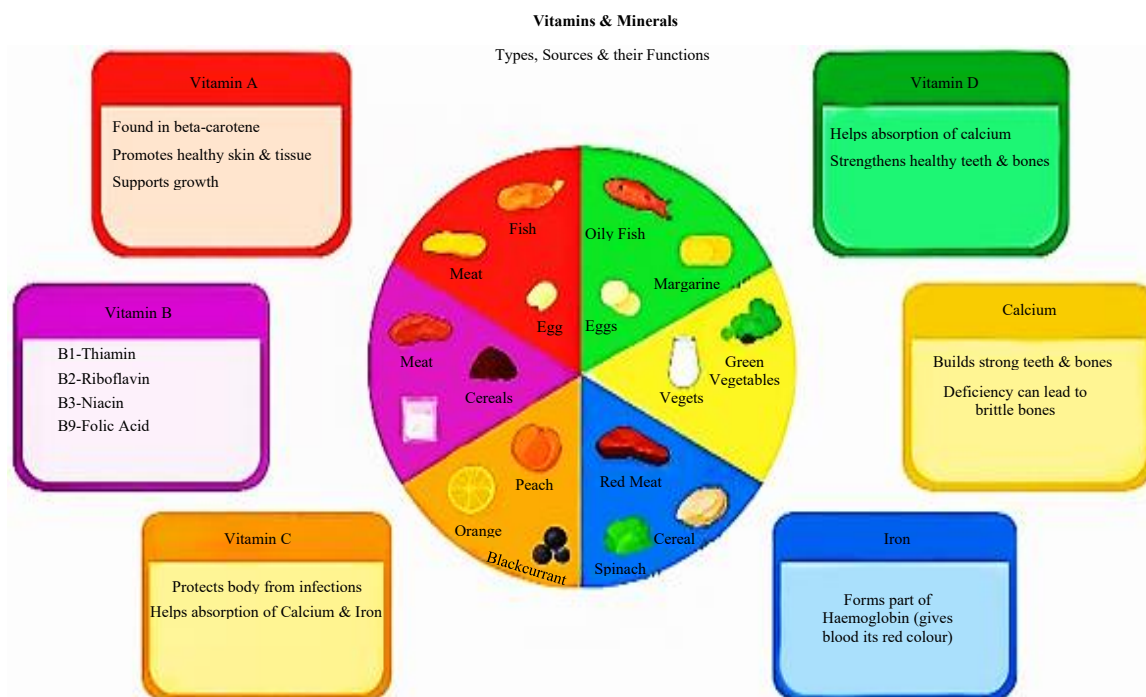


Figure 2. Vitamins & minerals.

Dietary Supplements

Dietary supplements are specially formulated products intended to complement the normal diet and provide additional nutrients or bioactive compounds that the body requires for proper functioning. They may be composed of one or more essential dietary ingredients and can exist in various forms such as capsules, tablets, powders, soft gels, or liquids. These supplements are designed to support health, maintain normal physiological processes, prevent deficiencies, and in some cases, enhance overall well-being. They can contain concentrates, constituents, extracts, or metabolites of naturally occurring substances. Unlike conventional foods, dietary supplements are consumed in measured doses and are not intended to replace a balanced diet but to work alongside it. They are also regulated differently from pharmaceutical drugs, as their main purpose is to promote nutrition and health rather than treat or cure diseases [5] (Figure 3).



Figure 3. Dietary supplements.

Functional Foods

Consumed as part of a regular diet; offer health benefits beyond basic nutrition [6]. Functional foods are like conventional foods but with physiological benefits and promote health and reduce the risk of diseases. The market for nutraceuticals and functional food is increasing drastically every year, and the global functional food market is expected to reach \$228.79 billion in 2025, although consumers buy these products from supermarkets. However, the difference between nutraceuticals, pharmaceuticals, medicinal foods, and functional foods is still confusing [7].

- *Nutraceuticals*: Isolated or purified food components taken in medicinal forms (capsules, tablets) for disease prevention/treatment.
- *Historical Roots*: Inspired by Hippocrates' quote "Let food be thy medicine..." and ancient civilizations like Egyptians and Chinese who used food medicinally [6] (Figure 4).



Figure 4. Functional food.

Designer Foods

Designer foods in the context of nutraceuticals refer to foods that have been intentionally modified, fortified, or engineered to provide specific health benefits beyond the basic nutritional value offered by conventional foods. The main goal of designer foods is to enhance the health-promoting properties of a food product so that it not only supplies essential nutrients but also assists in reducing the risk of chronic diseases or improving overall wellbeing. These foods can be altered through various processes such as fortification, where additional vitamins, minerals, or bioactive compounds are added, or through advanced biotechnological methods like genetic engineering to increase the presence of beneficial components. Designer foods maintain the appearance and consumption profile of regular dietary items, making them suitable for everyday intake without the need to change established eating habits. Within the nutraceutical framework, designer foods are seen as a strategy to combat nutrient deficiencies, prevent disease, and contribute to better health outcomes at a population level. They bridge the gap between nutrition and pharmaceuticals by delivering health benefits in a food matrix rather than in medicinal form. Regulatory bodies often categorize these foods together with functional and fortified foods. Designer foods represent an evolving frontier in public health nutrition, reflecting a targeted approach to disease prevention and health maintenance while seamlessly integrating into normal dietary practices [8] (Figure 5).



Figure 5. Designer food.

Medicinal foods

Medicinal foods in the context of nutraceuticals refer to those food products or their derived bioactive components that are specifically intended to offer not only nutritional value but also beneficial effects on health, particularly in the prevention, management, or treatment of certain diseases or medical conditions. These foods are often developed or processed in ways that enhance their potential to support health beyond basic nutrition, blurring the line between food and medicine. Medicinal foods in

nutraceuticals typically contain concentrated forms of specific nutrients, bioactive compounds, or phytochemicals that exert physiological or therapeutic effects. They are formulated to address health needs, targeting, for example, immune support, metabolic regulation, inflammation reduction, or other functional improvements in bodily systems. The concept recognizes that certain components in foods, when isolated or enriched and consumed at higher concentrations than typically found in the diet, can modify biological functions or processes in a manner similar to pharmaceutical substances, but with a focus on natural origins and preventive health (Figure 6). [9].



Figure 6. Medicinal food.

NUTRITIONAL DEFICIENCY DISORDERS

Cardiovascular Diseases

Cardiovascular diseases (CVD), including hypertension, coronary heart disease, stroke, heart failure, and peripheral vascular disease, are among the leading global health burdens, accounting for nearly one-third of worldwide deaths in 1999 and projected to be the primary cause of death in developing countries by 2010. Though largely preventable and controllable, CVD risk increases with poor dietary habits, particularly low intake of fruits and vegetables, while diets rich in these foods have shown protective effects. Nutraceuticals such as antioxidants, dietary fibers, omega-3 polyunsaturated fatty acids (n-3 PUFAs), vitamins, and minerals, combined with regular physical activity, play an important role in prevention and management of CVD. Polyphenols in grapes and wine, as well as flavonoids found in onion, cruciferous vegetables, citrus fruits, tea, berries, apples, cherries, buckwheat, milk thistle, and ginkgo, exhibit cardioprotective effects. These flavonoids work by blocking angiotensin-converting enzyme (ACE) to reduce blood pressure, inhibiting cyclooxygenase to prevent platelet aggregation, protecting the vascular system, and strengthening capillaries for better oxygen and nutrient delivery to cells.[31] cardiovascular disease (CVD) is common, indeed the majority of adults above sixty years of age will experience some manifestation of CVD. Based on data from 2012 and 2013, it has been estimated that CVD is responsible for 17.3 million deaths annually worldwide (1). Morbidity is also high, and in Europe, 200 billion Euros of healthcare expenditure is attributable to CVD (2). Risk factors for CVD can be categorized as modifiable and non-modifiable. Modifiable risk factors include obesity, hypertension, hyperlipidemia, diabetes mellitus, metabolic syndrome and lifestyle risk factors such as unhealthy diet, smoking and physical inactivity. Dietary factors are also important contributors to cardiovascular risk, either directly, or through their effects on other risk factors including hypertension, dyslipidemia and diabetes mellitus (3). Reduction of risk factors in the population, especially blood pressure reduction and lipid-lowering can have important impacts upon mortality from CVD. Cardiovascular disease (CVD) ranks among the most common health-related and economic issues worldwide. Dietary factors are important contributors to cardiovascular risk, either directly, or through their effects on other cardiovascular risk factors including hypertension, dyslipidemia and diabetes mellitus. Nutraceuticals are natural nutritional compounds, which have been shown to be efficacious in preventative medicine or in the treatment of disease. Several foods and dietary supplements have been shown to protect against the development of CVD [58].

- Deficiencies in vitamins (especially B-complex, C, A, D, and E) are strongly linked to cardiovascular diseases (CVD).
- *Vitamin B (B1, B2, B6, B9, B12)*: Deficiency leads to heart failure, high homocysteine, hypertension, atherosclerosis, and CAD. Supplementation works best in deficiency cases and B-complex is more effective than single vitamins.

- *Vitamin C*: A potent antioxidant; deficiency increases CAD, stroke, and MI risk. Beneficial mainly in ischemic heart disease by reducing oxidative stress and improving endothelial function.
- *Vitamin A (Retinol/ β -carotene)*: Shows antioxidant and anti-inflammatory benefits, reduces BP and atherosclerosis, but evidence in humans is inconclusive.
- *Vitamin D*: Deficiency is common and linked to hypertension, diabetes, heart failure, and MI. Supplementation shows mixed results; maintaining optimal levels may help prevent CVD.
- *Vitamin E*: Antioxidant with some protective effects in hypertension, atherosclerosis, and MI, but large trials show inconsistent or no benefit. High doses may even increase risk [59].

Hepatic Disease

Non-alcoholic fatty liver disease (NAFLD) is the most common chronic liver disorder and is considered the hepatic manifestation of metabolic syndrome. Its pathogenesis involves insulin resistance, lipid accumulation, oxidative stress, and multiple parallel factors such as genetics, cytokines, environment, and gut microbiota. The traditional “two-hit” hypothesis has been expanded into a “multiple parallel-hit” model to explain disease progression. Currently, weight loss and vitamin E (in non-diabetic NASH) are the only effective strategies, with no approved pharmacological treatments. Recently, nutraceuticals with antioxidant and anti-inflammatory properties have gained attention, showing potential benefits in liver function and histology [61] (Table 1).

Table 1. Principle nutraceutical for the treatment of non-alcoholic fatty liver diseases and target [60].

Nutraceutical	Main Actions / Targets
Vitamin E	Reduces oxidative stress; protects hepatocytes
Vitamin D	Modulates chronic inflammation; improves insulin resistance; corrects deficiency
Carnitine	Improves insulin resistance; reduces inflammation; hepatoprotective; affects lipid profile
Vitamin C	Antioxidant; hepatocellular protection
Omega-3 Fatty Acids	Improve dyslipidaemia; reduce cardiovascular risk; antioxidant; hepatocellular protection
Silymarin	Antioxidant; anti-inflammatory; improves insulin sensitivity; hepatoprotective

Cancer

Cancer remains a leading global cause of mortality, with projections estimating up to 18 million deaths by 2050. Its etiology is multifactorial, involving genetic mutations and environmental factors such as poor diet, chronic inflammation, and toxin exposure. Conventional treatments—surgery, chemotherapy, and radiation—often lack specificity, leading to adverse effects and eventual resistance. While advanced therapies like immunotherapy and gene therapy are emerging, their accessibility remains limited. In this context, nutraceuticals—bioactive dietary compounds delivered in non-food matrices—are gaining attention as adjunctive agents. They offer potential to enhance therapeutic outcomes, reduce side effects, and modulate key carcinogenic pathways including cell proliferation, apoptosis, angiogenesis, and inflammation. Carcinogenesis involves multiple biological processes, including uncontrolled cell proliferation, evasion of apoptosis (programmed cell death), angiogenesis (formation of new blood vessels), and chronic inflammation. Nutraceuticals have shown promise in modulating these pathways. Some exhibit antioxidant properties, reduce DNA damage, influence epigenetic mechanisms, restore tumour suppressor gene activity, and enhance immune surveillance. Others may impact gut microbiota, which plays a pivotal role in systemic inflammation and immune regulation [62].

Sourced predominantly from nature, nutraceuticals offer health benefits that extend beyond basic nutrition. They encompass a wide range of bioactive compounds, including.

- *Nutrients*: Vitamins, minerals, amino acids, and essential fatty acids.
- *Herbal products*: Garlic, ginger, goldenseal, melissa.
- *Dietary supplements*: Black cohosh, ginkgo biloba, glucosamine.
- *Probiotics*: *Bifidobacterium*, *Lactobacillus*.
- *Prebiotics*: Galacto-oligosaccharides, inulin [62].

Common examples include lycopene from tomatoes, omega-3 fatty acids from salmon, and saponins from soy. Fortified foods—such as calcium-enriched orange juice and folic acid-enriched flour—also serve as functional sources of nutraceuticals

Melatonin in Cancer Prevention and Treatment

- *Early Research:* For over 30 years, studies (notably by Lissoni) have shown high-dose melatonin can slow tumour growth, improve quality of life, and enhance chemotherapy response in metastatic cancers.
- *Mind-Body Link:* Melatonin's benefits were stronger in patients with spiritual faith, highlighting the role of mindset in immune response (psycho-immune-neuroendocrinology).
- *Circadian Rhythm:* Cancer patients (e.g., breast, colorectal) often have disrupted circadian rhythms [6].
- *Biochemical Role:* Stress and high cortisol shift tryptophan metabolism away from serotonin/melatonin toward kynurenine, leading to inflammation, fatigue, anemia, and depression. Supplementation with melatonin may counteract this.
- *Night-Shift Workers:* Light exposure at night disrupts circadian rhythm, increasing breast cancer risk. Melatonin reduces tumor proliferation, survival, metastasis, and drug resistance (suppressing the Warburg effect).
- *Molecular Effects:* Meta-analysis shows melatonin influences 46 microRNAs across multiple cancers, enhancing immune/apoptotic genes while downregulating tumor survival, angiogenesis, and metastasis [63].

Obesity

Obesity is a prevalent global health problem characterized by excessive fat accumulation, typically defined by BMI ≥ 30 kg/m². It increases risks for diabetes, cardiometabolic dysfunction, disability, malignancy, and premature mortality. Management includes lifestyle changes, surgery, pharmacological treatments, and dietary supplements. Due to their low toxicity and accessibility, dietary supplements are increasingly popular for weight loss, especially among young adults, women, and lower socioeconomic groups.

Mechanisms and Categories of Dietary Supplements

Dietary supplements for obesity contain a variety of ingredients such as minerals, vitamins, amino acids, herbs, and plant extracts. Their mechanisms to aid weight loss include.

- Reducing appetite or food intake.
- Inhibiting fat and glucose absorption.
- Increasing metabolic rate and energy expenditure.
- Promoting lipolysis (fat breakdown).
- Reducing lipogenesis (fat synthesis).

Key Dietary Supplements with Evidence for Weight Loss

- *β -Glucans:* Soluble fibres that increase satiety and reduce glucose absorption; show secondary benefits in insulin sensitivity and lipid profiles.
- *Bitter Orange (*Citrus aurantium*):* Contains synephrine, increases metabolic rate safely up to 98 mg/day.
- *Calcium and Vitamin D:* Improve metabolism and adipocyte function, promoting fat loss.
- *Chitosan:* A marine fiber that binds fats to prevent absorption, supported by meta-analyses showing modest weight loss
- *Chromium:* Enhances insulin sensitivity and regulates satiety-related neurotransmitters, aiding fat loss while preserving lean mass.
- *Cocoa:* Contains methylxanthines and polyphenols that stimulate thermogenesis and lipid breakdown.

- *Coleus forskohlii*: Stimulates lipolysis via cAMP activation, with some evidence of fat loss and increased lean mass.
- *Conjugated Linoleic Acid (CLA)*: Reduces hunger and improves lipid metabolism.
- *Ephedra sinica*: Increases metabolic rate, though mainly effective short-term.
- *Fucoxanthin*: A marine carotenoid that reduces lipogenesis, increases thermogenesis, and improves lipid metabolism.
- *Garcinia cambogia*: Inhibits fat synthesis enzyme ATP-citrate lyase, reducing lipogenesis.
- *Glucomannan*: A soluble fiber that increases satiety and reduces fat absorption; clinical evidence is mixed.
- *Green coffee extract*: Contains chlorogenic acid, reduces lipase activity and enhances fat metabolism.
- *Green tea*: Contains caffeine and catechins that suppress appetite and increase thermogenesis.
- *Guar Gum*: A dietary fiber that delays gastric emptying but with inconsistent efficacy and some gastrointestinal side effects.
- *Hoodia gordonii*: Traditionally used appetite suppressant; active compounds increase hypothalamic ATP, though oral use requires high doses due to breakdown in the stomach.
- *Irvingia gabonensis (African mango)*: Inhibits fat cell formation, improves lipid and weight parameters, but is based mostly on African populations.
- *Raspberry Ketones*: Increase fat oxidation and reduce fat accumulation in vitro; clinical evidence is limited, and safety concerns exist.
- *Phenylpropylamine*: A sympathomimetic reducing appetite and promoting weight loss without notable side effects.
- *Pyruvate*: Involved in energy metabolism, may promote weight loss but can cause gastrointestinal discomfort [64].

Mechanisms of Action

- Appetite suppression (e.g., fibers, *Hoodia gordonii*).
- Reduced fat absorption (e.g., chitosan, white kidney bean).
- Enhanced fat burning and thermogenesis (green tea catechins, caffeine, capsaicin).
- Improved glucose/lipid metabolism (chromium, calcium + vitamin D) (Figure 7).

$$\text{BMI} = \frac{\text{Weight in kilogram}}{(\text{Height in meter})^2}$$

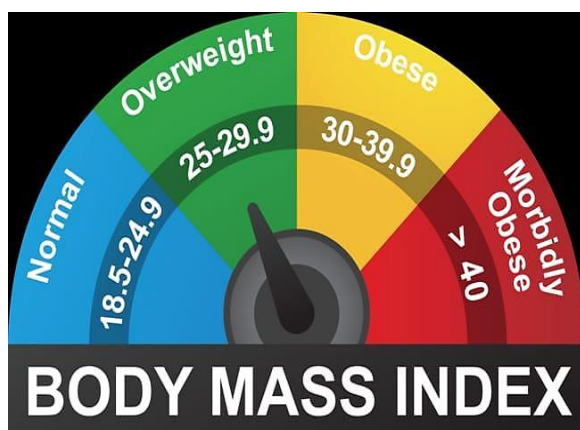


Figure 7. Body mass index.

Clinical Evidence

- Some nutraceuticals show promising results in reducing body weight and fat mass.
- Evidence is still mixed and limited; results vary across studies.

Safety Concerns

- Generally safe when consumed moderately.
- *Side effects*: gastrointestinal discomfort, cardiovascular risks (with stimulants like synephrine) [65].

Osteoarthritis (OA)

Osteoarthritis (OA) is characterized by cartilage breakdown causing joint pain and stiffness. Commonly affected joints include knees, hips, hands, and spine. Standard OA treatments include acetaminophen, NSAIDs, tramadol, corticosteroid injections, and sometimes duloxetine. Interest in dietary supplements for OA has grown, including curcuma (curcumin/turmeric), known for anti-inflammatory effects.

Knee OA is the most common type of osteoarthritis (85% of OA cases globally).

- *Major risk factors*: female sex, obesity, past knee injury, malalignment, weak knee muscles.
- *Current treatments*: lifestyle changes, physiotherapy, medications (NSAIDs, corticosteroids), and complementary & alternative medicines (CAMs). Supplements are being explored as safer long-term options.

Glucosamine & Chondroitin

- Important for cartilage matrix formation.
- May reduce cartilage breakdown and slow disease progression.
- Strong recommendation for chondroitin sulfate (1.2 g/day) from EULAR guidelines [66].

Methyl Sulfonyl Methane (MSM)

- Anti-inflammatory properties.
- Some studies show improved pain/function, others show no benefit [66].

Curcumin (Turmeric component)

- Major active compound of turmeric (with curcuminoids).
- Inhibits NF- κ B and inflammatory cytokines, protects chondrocytes, reduces apoptosis, COX-2, and prostaglandins.
- Low oral bioavailability → improved with liposomes, nanoparticles, Theracurmin, or Piperine (↑ 2000%).
- *Clinical studies*: effective as NSAIDs (Diclofenac), improves WOMAC scores, pain, and function.
- *Side effects*: dyspepsia, nausea, loose stools, edema [67].

Fish Oil (EPA & DHA)

- Anti-inflammatory effects on cartilage.
- *Studies*: Low dose (1000 mg) better than higher dose (2000 mg).
- Some trials showed improved function and reduced pain, but evidence is inconsistent and of low quality
- *Side effects*: diarrhea, reflux, intolerance.
- Standardization required for reliable results [67].

Diacerein

- Reduces IL-1 β , TNF- α , MMP-13.
- Works similar to NSAIDs but has side effects (diarrhea, liver issues) → restricted use in EU/US

Avocado-Soybean Unsaponifiable (ASU / Piascledine)

- Inhibits inflammation and stimulates collagen synthesis [66].

Ginger

- Traditional anti-inflammatory herb.

- Reduces inflammatory markers (CRP, NO, cytokines).
- *Clinical studies*: Significant pain reduction, especially when combined with Diclofenac.
- Shown to slow joint space narrowing and improve symptoms [67].

EYE

The eye is one of the most important sensory organs of the human body. It enables us to perceive the world through the sense of vision, which is essential for almost all daily activities such as reading, writing, learning, driving, and working. Vision also plays a key role in social interaction, communication, and quality of life. The eye functions like a camera. Light rays from objects enter the eye through the cornea and lens, where they are refracted (bent) and focused onto the retina at the back of the eye. The retina contains specialized light-sensitive cells called rods and cones:

- Rods help in vision under dim light (night vision).
- Cones are responsible for colour vision and fine detail.

These cells convert light into electrical impulses, which are carried to the brain by the optic nerve. The brain then interprets these signals, allowing us to form images and recognize the world around us. Because of its delicate structure and constant exposure to the external environment, the eye is vulnerable to many problems such as infections, injuries, nutritional deficiencies, refractive errors, and degenerative diseases. If not treated early, these can result in visual impairment or permanent blindness. According to the WHO, a large percentage of blindness worldwide is preventable with proper awareness, early detection, and timely treatment [68].

Common Eye Disorders

- *Refractive errors*: Myopia, hypermetropia, astigmatism, presbyopia.
- *Cataract*: Clouding of lens, common in elderly.
- *Glaucoma*: Increased intraocular pressure damaging optic nerve.
- *Conjunctivitis*: Inflammation of conjunctiva (allergic, bacterial, viral).
- *Trachoma*: Infectious cause of blindness.
- *Night Blindness*: Vitamin A deficiency [69].

Nutraceuticals for Eye Disease

- *Traditional nutraceuticals*: From natural sources (plants, animals, microbes).
- *Phytochemicals*: polyphenols, carotenoids, quinones, organosulfur compounds, saponins, alkaloids.
- *Nutrients*: peptides, carbohydrates, fatty acids, vitamins (A, B12, C, D), minerals (zinc, selenium).
- *Herbals*: e.g., cranberries, lavender, willow bark.
- Enzymes & probiotics
- *Non-traditional nutraceuticals*: Biotech-based (recombinant, fortified foods like calcium-fortified milk, folic acid flour, iodized salt).

Advantages of Nutraceuticals

- Natural, fewer side effects compared to drugs.
- Provide antioxidant, anti-inflammatory, neuroprotective, and anti-angiogenic benefits [68].

Diabetes Mellitus (DM)

Diabetes mellitus (DM), one of the most serious non-communicable diseases, has long-term negative effects on the healthcare system due to its microvascular and macrovascular manifestations, which can be fatal if left untreated. Nutraceuticals, on the other hand, are alternative therapy choices of orally consumed natural food ingredients applicable in the management of several diseases, including diabetes mellitus. Through their antioxidant capabilities and bioactive components, nutraceuticals have been clinically demonstrated to be effective in preventing a number of ailments, including cancer, diabetes, heart disease, and kidney problems.

Nutraceuticals such as fenugreek, bitter melon, gymnema, cinnamon, chromium, magnesium, omega-3 fatty acids, curcumin, resveratrol, and soluble fibers are widely studied for Diabetes Mellitus management. They help lower blood glucose, improve insulin sensitivity, and prevent diabetic complications [70].

Plant-Derived Compounds

- *Fenugreek (Trigonella foenum-graecum)*: Rich in soluble fiber → slows glucose absorption, improves insulin sensitivity.
- *Bitter melon (Momordica charantia)*: Contains charantin, vicine, polypeptide-p → insulin-like activity.
- *Gymnema sylvestre* (“*Sugar destroyer*”): Reduces glucose absorption, enhances insulin secretion.
- *Cinnamon*: Improves insulin receptor sensitivity, glucose uptake.
- *Garlic & Onion (Allium species)*: Sulfur compounds stimulate insulin secretion.
- *Banaba (Lagerstroemia speciosa)*: Contains corosolic acid → reduces blood sugar.
- *Green Tea (Catechins, EGCG)*: Improves glucose metabolism, antioxidant activity.
- *Curcumin (from Turmeric)*: Anti-inflammatory, enhances β -cell survival.

Vitamins & Minerals

- *Chromium picolinate*: Improves insulin action and glucose metabolism.
- *Magnesium*: Enhances insulin sensitivity.
- *Vitamin D*: Regulates insulin secretion and β -cell function.
- *Vitamin E & C*: Antioxidant protection against diabetes complications.

Polyphenols & Antioxidants

- *Resveratrol (from grapes, berries)*: Improves insulin sensitivity, reduces oxidative stress.
- *Quercetin (from onions, apples)*: Antioxidant, improves glucose uptake.
- *Alpha-lipoic acid*: Potent antioxidant, prevents diabetic neuropathy.

Fatty Acids

- *Omega-3 fatty acids (Fish oil, Flaxseed, Chia)*: Improve lipid profile, reduce inflammation in diabetes.
- *Conjugated linoleic acid (CLA)*: Improves glucose metabolism.

Fibers & Others

- *Guar gum, Psyllium husk*: Soluble fibers that slow glucose absorption.
- *Probiotics & Prebiotics*: Improve gut microbiota, may enhance insulin sensitivity [71–73].

SKIN

Nutraceuticals, which are foods or food-derived substances offering health or therapeutic benefits, play an important role in maintaining skin wellness and promoting graceful skin ageing. Research shows they contribute to collagen production, renewal of skin cells, reduction of inflammation, antioxidant defense, protection against UV damage, and improved skin hydration [74].

Nutraceuticals, defined as foods or food components that provide medical or health benefits, can optimize skin health and support healthy skin ageing. Evidence highlights their role in collagen synthesis, skin cell renewal, anti-inflammatory and antioxidant effects, sun protection, and hydration. The article stresses the importance of recommending well-researched, bioavailable nutrients at effective doses. Combined with a balanced diet and quality cosmeceuticals, nutraceuticals contribute to a comprehensive approach for improving skin health and delaying ageing.

Skin acts as the body's first defense against UV radiation, chemicals, and microbes. Micronutrients (vitamins, minerals, bioactive compounds) are essential for maintaining skin structure, barrier function, and healing [75].

Key Supplements & Their Roles

- Vitamin A – Supports immune defence, collagen production, acne treatment, and anti-aging.
 - Vitamin C – Strong antioxidant, collagen booster, photoprotection, and wound healing.
 - Vitamin E – Antioxidant, anti-inflammatory, improves psoriasis and atopic dermatitis.
 - Vitamin D – Immune regulation, barrier repair, beneficial in psoriasis, vitiligo, and atopic dermatitis.
 - Curcumin – Anti-inflammatory, antioxidant, improves acne, psoriasis, and wound healing.
 - Polypodium leucotomos – Fern extract with photoprotective and antioxidant effects; prevents UV damage.
 - Simmondsia chinensis (Jojoba oil) – Moisturizing, anti-inflammatory, supports wound healing and drug delivery.
 - Biotin (Vitamin B7) – Supports skin, hair, and nail health; deficiency causes dermatitis and hair loss.
 - Gamma Oryzanol – From rice bran; antioxidant, anti-aging, and sun-protective.
 - Olive Leaf Extract – Rich in polyphenols; antiviral, antibacterial, antioxidant, and photoprotective.
 - Spirulina – Cyanobacteria with antioxidant, anti-aging, wound-healing, and immune-boosting effects.
 - Chlorella – Algae rich in vitamins and minerals; boosts collagen, antioxidants, and anti-inflammatory.
 - Omega-3 Fatty Acids – Anti-inflammatory, improve atopic dermatitis, psoriasis, and protect against UV damage.
 - Astaxanthin – Potent antioxidant carotenoid; reduces wrinkles, improves elasticity, protects against UV.
- Key findings from human studies
- *Bioactive peptides (collagen peptides)*: Improve skin elasticity, reduce wrinkles, and enhance collagen and elastin synthesis.
 - *Polysaccharides (e.g., Imedeen®, Vivida®)*: Enhance hydration, elasticity, and thickness; results vary with sample size and study design.
 - *Botanical extracts (e.g., Pycnogenol®, Aloe sterols, citrus/rosemary blends)*: Show antioxidant, photoprotective, anti-ageing, and pigmentation-improving effects, though many trials use small groups.
 - *Carotenoids (β-carotene, lycopene, lutein)*: Offer modest photoprotection, increase MED (Minimal Erythema Dose), and improve pigmentation.

Benefits for Skin Health

- Anti-aging (collagen stimulation, wrinkle reduction).
- Photoprotection (defense against UV-induced damage).
- Anti-inflammatory effects (useful in psoriasis, atopic dermatitis, acne).
- Support for wound healing and barrier repair.
- Potential role in cancer prevention and therapy support [76].

Asthma

- Asthma is a chronic inflammatory airway disorder with rising prevalence since the 1980s.
- Risk is higher in children, older adults, African Americans, and low-income groups.
- *Standard treatment*: inhaled corticosteroids, β-agonists, oral medications, plus environmental control.

Dietary Factors and Asthma

Fruits & Vegetables

- Higher intake is consistently linked to reduced asthma risk and symptoms (wheezing, exacerbations).
- Specific benefits seen with apples, oranges, citrus fruits.
- Raw vegetables seem more protective than cooked (flavonoids lose effect with heating).
- *Mechanism:* antioxidant and anti-inflammatory effects.

Dairy Products

- *Mixed but generally show a negative effect:* higher dairy intake linked with increased asthma risk and bronchial hyperreactivity.
- Some clinical trials show small but significant declines in lung function after cow's milk intake.
- Possible role of milk proteins/lipids in triggering inflammation (e.g., IL-17F pathway).

Western Diet

- High in animal products, fat, and low in fiber/plant foods.
- Associated with worse lung function and higher airway inflammation (↑ eosinophils, cytokines).
- Urbanization and Western diet adoption linked to rising asthma prevalence.

Plant-Based & Mediterranean Diets

- Emphasize fruits, vegetables, legumes, whole grains, and reduced meat/dairy.
- Linked to lower asthma prevalence, improved lung function (FEV1, FVC), fewer hospital admissions, and less medication use.
- Vegan diets show improvements in symptom severity and medication reduction.

Potential Mechanisms

Antioxidants (Vitamin C, E, carotenoids, flavonoids, selenium): reduce oxidative stress and airway inflammation. *Anti-inflammatory nutrients (unsaturated fatty acids, plant compounds):* lower pro-inflammatory cytokines, improve immune regulation. *Weight management:* plant-based diets may reduce obesity, a risk factor for asthma.

Oxidative stress arises from both endogenous sources (mitochondrial respiration, peroxisomes, inflammatory cells, arachidonic acid metabolism) and exogenous sources (ozone, cigarette smoke, xenobiotics). The body counters these with antioxidant defenses, which include dietary antioxidants (vitamins C, E, carotenoids, selenium, α -lipoic acid) and endogenous enzymes (SOD, CAT, HMOX1, glutathione peroxidase, glutathione system) (Figure 8).

CNS

Neurological disorders (Alzheimer's, Parkinson's, depression, psychosis, etc.) are increasing worldwide due to aging, lifestyle changes, and diet. Conventional treatments often cause side effects, so safer alternatives are being explored. Nutraceuticals—bioactive compounds from food and herbs—offer neuroprotective benefits through antioxidant, anti-inflammatory, and cognitive-enhancing properties.

Types of Nutraceuticals

- *Food-based (traditional):* Nutrients (vitamins, minerals, fatty acids), herbs (turmeric, ginkgo, ashwagandha), probiotics, enzymes.
- *Non-traditional:* Fortified and recombinant foods (e.g., calcium-fortified juice, vitamin-enriched cereals).
- *By mechanism:* Antioxidants, anti-inflammatory, antibacterial, antifungal, anti-obesity agents.
- *By chemical nature:* Fatty acids, amino acids, polyphenols, carotenoids, etc.

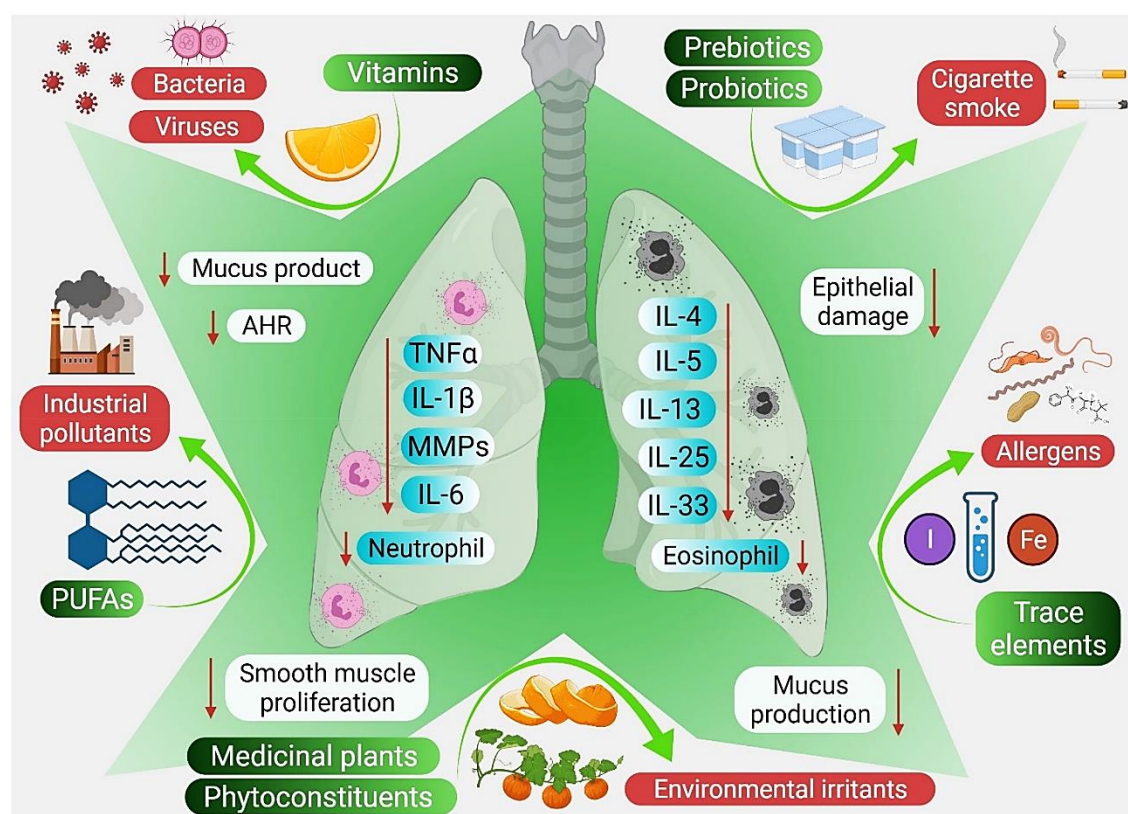


Figure 8. Potential mechanisms.

Nutraceutical Roles in Major Neurological Disorders

Neurodegeneration (General Mechanisms)

- *Cause:* Disorders like Alzheimer's, Parkinson's, and epilepsy arise from protein misfolding (tau, amyloid- β , α -synuclein), oxidative stress, mitochondrial dysfunction, and chronic inflammation.

Nutraceutical Actions

- Antioxidants (e.g., quercetin, kaempferol, bacosides) reduce free radicals, preventing neuronal damage.
- Anti-inflammatory compounds (with nine from ashwagandha, Asiatic acid from gotu kola) suppress cytokines and enzymes (COX, iNOS) that drive neuroinflammation.
- Neuroprotective phytochemicals like brahmine (*Bacopa monnieri*) stabilize synaptic transmission, enhance memory, and reduce glycation products that worsen oxidative damage.
 - *Outcome:* Slow down degeneration, protect mitochondria, and support cognitive functions.

Alzheimer's Disease (AD)

- *Cause:* Accumulation of amyloid plaques, tau tangles, and excessive oxidative stress.

Nutraceutical Interventions

- Flavonoids (catechin, epicatechin, epigallocatechin) from tea, cocoa, and fruits enhance cerebral blood flow, modulate glial signaling, and support synaptic plasticity.
- Carotenoids (lutein, zeaxanthin, lycopene, astaxanthin) act as antioxidants and protect mitochondria; low levels are linked with worsening AD.
- Crocin (from saffron) enhances cognition and memory, reduces oxidative markers in the hippocampus, and helps in mild-to-moderate AD.
- Cyanidin (anthocyanins) from berries suppress inflammatory cytokines and prevent neuronal cell death.

- Luteolin and apigenin (flavones in parsley, rosemary, celery) protect DNA, reduce oxidative damage, and prevent neuroinflammation.
 - *Outcome:* Nutraceuticals in AD delay disease progression, improve memory and cognition, and reduce oxidative and inflammatory burden.

Parkinson's Disease (PD)

- *Cause:* Degeneration of dopaminergic neurons in the substantia nigra due to mitochondrial dysfunction, oxidative stress, α -synuclein aggregation, and neuroinflammation.

Nutraceutical Interventions

- Omega-3 fatty acids (EPA, DHA from fish oil) improve neuronal membrane fluidity, protect mitochondria, and reduce inflammation.
- Coenzyme Q10 (CoQ10) supports ATP production in mitochondria, prevents oxidative damage, and slows motor symptoms.
- Lycopene (from tomatoes) acts as an antioxidant, increases dopamine levels in the striatum, and improves neurobehavioral function.
- Epigallocatechin gallate (EGCG) from green tea crosses the blood–brain barrier, scavenges radicals, and improves motor function.
- Ginsenosides (from ginseng) regulate glutathione, reduce ROS, and protect dopaminergic neurons
- Vincamine and vinpocetine (from Vinca plant) enhance cerebral blood flow, protect against ROS, and maintain dopamine synthesis.
- Resveratrol & Baicalein modulate autophagy, prevent α -synuclein fibrillation, and reduce neuronal apoptosis.
 - *Outcome:* Nutraceuticals in PD provide neuroprotection, improve motor function, reduce oxidative stress, and may complement existing drugs.

Depression

- *Cause:* Imbalance in neurotransmitters (serotonin, dopamine, norepinephrine), oxidative stress, inflammation, and impaired neurogenesis.

Nutraceutical Interventions

- Omega-3 fatty acids inhibit monoamine reuptake, increase membrane fluidity, reduce inflammation, and enhance neurogenesis.
- N-acetyl cysteine (NAC) replenishes glutathione, reduces oxidative stress, modulates glutamate signaling, and protects mitochondria.
- *S-adenosyl methionine (SAME):* Acts as a methyl donor, regulates neurotransmitter synthesis, and reduces depressive symptoms.
- *L-Tryptophan / 5-HTP:* Precursors of serotonin; supplementation boosts serotonin levels and works synergistically with antidepressants.
- *Vitamin D:* Regulates genetic expression of enzymes like tyrosine hydroxylase, influencing dopamine production; deficiency is linked to depression.
- *Zinc:* Enhances hippocampal neurogenesis and modulates glutamate/NMDA receptors, improving mood.
- *St. John's Wort (Hypericum perforatum):* Rich in hyperforin and hypericin, inhibits monoamine oxidase and reuptake of serotonin, norepinephrine, and dopamine.
- *Outcome:* Nutraceuticals in depression improve mood, neurotransmission, and brain plasticity, either alone or as adjunctive therapy.

Psychotic Disorders (Schizophrenia & Bipolar Disorder)

- *Cause:* Dysregulation of dopamine and serotonin pathways, oxidative stress, mitochondrial dysfunction, and chronic inflammation.

Nutraceutical Interventions

- *Omega-3 fatty acids (EPA, DHA)*: Enhance dopaminergic and serotonergic signaling, regulate brain-derived neurotrophic factor (BDNF), reduce microinflammation, and stabilize membranes.
- *Vitamins (B-complex, D, C, E)*: Act as antioxidants, co-factors in neurotransmitter synthesis, and protect against oxidative damage.
- *Adjunctive effect*: Nutraceuticals amplify therapeutic efficacy of antipsychotic medications while seducing their side effects.
 - *Outcome*: Better symptom management, reduced oxidative stress, and improved long-term prognosis in psychosis [80, 81, 30].

Gynaecology and Fertility

Nutrition plays a vital role in women's reproductive health. Poor diet and nutrient deficiencies are linked to several gynaecological problems. Nutrients can also influence gene expression and disease risk through epigenetic changes. Many benign conditions like PCOS, endometriosis, fibroids, and malignant cancers are impacted by diet.

Infertility

- *Mediterranean diet*: Improves IVF outcomes and fertility due to plant-based proteins, healthy fats, and low-glycaemic carbs.
- *Fats*: Monounsaturated fats support conception, while excess polyunsaturated fats may worsen ovulatory issues.
- *Vitamins & antioxidants*: Vitamin C, E, beta-carotene linked to shorter time to pregnancy, depending on BMI and age.
- *Probiotics*: Lactobacilli help protect vaginal health and may improve fertility.

Polycystic Ovary Syndrome (PCOS)

Strongly linked with insulin resistance and obesity.

Dietary Management

- Reduce high-glycemic carbs and saturated fats.
- Increase omega-3 intake.
- Vitamin D improves insulin sensitivity and ovarian function.
- *Natural anti-androgen foods*: Soy, green tea, and licorice lower testosterone.
- Flavonoids (quercetin, resveratrol) improve metabolic and hormonal balance.
 - *Minerals*: Chromium, calcium, selenium, zinc, and magnesium improve insulin resistance and reproductive function.

Uterine Fibroids

- Most common gynecological tumors in reproductive-age women.
- *Fats*: High trans fats and marine ω -3 intake linked to higher fibroid risk; healthier fat balance may help.
- *Fruits & vegetables*: Citrus fruits and carotenoids reduce fibroid risk; antioxidants and phytochemicals inhibit fibroid cell growth.
- *Green tea extract (EGCG)*: Shown to shrink fibroid size.
- *Dairy & Vitamin D*: Higher dairy intake and vitamin D protect against fibroids.
- *Pollutants & heavy metals*: Endocrine-disrupting chemicals (e.g., BPA, cadmium, lead) increase fibroid risk.

Endometriosis

- Estrogen-dependent inflammatory disease linked to pain and infertility.
- Omega-3 reduces inflammation and endometrial growth, while omega-6 (red meat) worsens it.

- Vitamin D regulates immune responses and reduces pain in some studies.
- N-acetylcysteine (from garlic, onions, broccoli) reduces cyst size.
- Flavonoids (quercetin, resveratrol, sulforaphane) show anti-inflammatory and anti-proliferative effects.
- L-carnitine has mixed effects depending on estrogen receptor status.

Vaginal Microbiome & Infections

- Healthy vaginal flora (dominated by *Lactobacillus*) protects against infections.
- Bacterial vaginosis (BV) is linked to vitamin deficiencies (A, C, D, E, folate, calcium) and high-fat/sugar diets.
- Vitamin D deficiency strongly associated with BV.
- Poor diet alters microbiome, increasing risks of HIV, HPV, preterm birth, and cancers.

Gynaecological Cancers

- *Cervical cancer*: Caused by HPV; antioxidants (vitamins A, C, E, carotenoids, green tea, curcumin, resveratrol) may reduce persistence and progression.
- *Endometrial cancer*: Obesity and high-fat diets increase risk. Isoflavones (soy), green tea catechins, and flavonoids may offer protective effects, but evidence is mixed.
- *Ovarian cancer*: Linked with chronic inflammation and high fat intake. Diets rich in cruciferous vegetables, flavonoids (quercetin, kaempferol), and curcumin show potential protective effects.

CONCLUSION

In an era where health challenges are increasingly complex and lifestyle-driven, nutraceuticals have emerged as a promising bridge between nutrition and medicine. This review underscores their multifaceted roles—not merely as dietary supplements, but as strategic agents in disease prevention, therapeutic support, and overall wellness enhancement. From vitamins and minerals to bioactive compounds and designer foods, nutraceuticals offer targeted benefits across cardiovascular, hepatic, metabolic, neurological, and dermatological domains. Yet, their efficacy hinges on evidence-based use, regulatory oversight, and personalized integration into clinical practice. Rather than viewing nutraceuticals as miracle cures or replacements for conventional therapy, they should be embraced as complementary allies—rooted in nature, refined by science, and guided by responsible application. As research advances and consumer awareness grows, the future of nutraceuticals lies in precision, safety, and synergy with holistic health strategies. The document emphasizes that nutraceuticals serve as a vital link between food and medicine, offering natural, bioactive compounds that play an important role in both the prevention and management of various diseases. Unlike pharmaceuticals, which are synthetic and primarily used to treat or cure specific illnesses, nutraceuticals—derived from food sources such as vitamins, minerals, herbs, and functional foods—aim to maintain health, prevent disease onset, and support physiological balance with fewer side effects. They have demonstrated significant potential in managing chronic conditions such as cardiovascular diseases, diabetes, liver disorders, cancer, and obesity through their antioxidant, anti-inflammatory, and metabolic regulatory properties. While pharmaceuticals act rapidly and target specific disease mechanisms, nutraceuticals work gradually, improving overall health and resilience by correcting nutritional imbalances and enhancing body functions. Therefore, nutraceuticals and pharmaceuticals should be viewed as complementary approaches—nutraceuticals focusing on long-term health promotion and disease prevention, and pharmaceuticals providing precise and curative treatment. A balanced integration of both can lead to safer, more effective, and holistic healthcare management.

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