Journal of Pharmacognosy and Phytochemistry
Available online at www.phytojournal.com

E-ISSN: 2278-4136
P-ISSN: 2349-8234
Impact Factor (RJIF): 6.35
www.phytojournal.com
JPP 2025; 14(5): 328-335
Received: 05-06-2025
Accepted: 08-07-2025

Tanvi Patel
Student, Department of Pharmacognosy, Sharda School of Pharmacy, affiliated to Gujarat Technological University, Pethapur, Gandhinagar, Gujarat, India

Yugmi Patel
Student, Department of Pharmacognosy, Sharda School of Pharmacy, affiliated to Gujarat Technological University, Pethapur, Gandhinagar, Gujarat, India

Mansi Patel
Student, Department of Pharmacognosy, Sharda School of Pharmacy, affiliated to Gujarat Technological University, Pethapur, Gandhinagar, Gujarat, India

Damini Patel
Student, Department of Pharmacognosy, Sharda School of Pharmacy, affiliated to Gujarat Technological University, Pethapur, Gandhinagar, Gujarat, India

Divyakant Patel
Head of the Institute, Sharda School of Pharmacy, affiliated to Gujarat Technological University, Pethapur, Gandhinagar, Gujarat, India

Khushboo Vaghela
Professor, Department of Pharmacognosy, Sharda School of Pharmacy, affiliated to Gujarat Technological University, Pethapur, Gandhinagar, Gujarat, India

Corresponding Author:
Khushboo Vaghela
Professor, Department of Pharmacognosy, Sharda School of Pharmacy, affiliated to Gujarat Technological University, Pethapur, Gandhinagar, Gujarat, India

Biosynthetic pathways in plants: A gateway to natural products and drug discovery

Tanvi Patel, Yugmi Patel, Mansi Patel, Damini Patel, Divyakant Patel and Khushboo Vaghela

DOI: https://www.doi.org/10.22271/phyto.2025.v14.i5e.15589

Abstract
Biosynthesis, also termed anabolism, is a fundamental biological process wherein living organisms synthesize complex macromolecules from simple precursors through enzyme-catalyzed reactions, often requiring cofactors such as ATP, NADH, and NADPH. Primary metabolites, including sugars, amino acids, and fatty acids, sustain growth and physiological development, while secondary metabolites such as alkaloids, flavonoids, and glycosides arise from primary pathways and confer ecological and pharmacological advantages. Central metabolic pathways like glycolysis, the pentose phosphate pathway, and photosynthesis provide essential precursors for these biosynthetic reactions. Secondary metabolite biosynthesis is primarily governed by three major pathways: the shikimic acid pathway, which yields aromatic amino acids and phenylpropanoids with roles in plant defense and as pharmaceutical precursors (e.g., oseltamivir, alkaloids, flavonoids); the acetate-mevalonate pathway, central to terpenoid and steroid biosynthesis, also representing the pharmacological target of statins; and the acetate-malonate (polyketide) pathway, which produces fatty acids and diverse polyketides, including clinically vital antibiotics, anticancer agents, and immunosuppressants. Advances in metabolic engineering, combinatorial biosynthesis, and engineered host systems have expanded the scope of these pathways for drug discovery and industrial applications. Understanding biosynthetic mechanisms provides critical insights into natural product chemistry, plant defense systems, and therapeutic innovation in pharmacognosy.

Keywords: Biosynthesis, Shikimic acid pathway, Acetate pathway

Introduction
The process by which tiny organic subunits within a living creature are converted into bigger organic substances is known as biosynthesis. Enzymes are primarily responsible for biosynthesis. Anabolism is another name for biosynthesis because enzymes combine simple molecules to create macromolecules. For instance, the chloroplast is where photosynthesis takes place. Photosynthesis transforms the energy of light into chemical energy. Water and carbon dioxide are converted into the bigger molecule glucose by photosynthetic organisms (ATP, Enzyme, Cofactors). We discovered that all 20 amino acid biosynthesis routes were fully restored in Escherichia coli, Bacillus subtilis, and most likely in synechocystis. However, a broader substrate specificity for aspartate amino transfers had to be assumed. Element of biosynthesis include: precursor compounds, chemical energy (e.g. ATP), and catalytic enzymes which may need coenzymes (e.g. NADH, NADPH) [1]. The building blocks of macromolecules, monomers, are produced by these elements. Important biological macromolecules include DNA molecules, which are made up of nucleotides connected by phosphoryl di ester linkages, and proteins, which are made up of amino acid monomers united by peptide bonds. The artificial creation of macromolecules from small molecules is known as synthesis. Synthesis is a chemical and artificial process. Both organic and non-organic polymers can be produced using synthesis. Synthesis takes place outside of living things. The process by which tiny molecules within a living creature are converted into larger organic substances is known as biosynthesis. Enzymes catalyze the biological process of biosynthesis. Biosynthesis takes place in living things [2].

Biosynthesis of Primary Metabolites
Air, water, minerals, and sunlight are all used to create primary and secondary metabolites in living plants, which are solar-powered biochemical and biosynthetic laboratories. Sugars, amino acids, and fatty acids are examples of the main metabolites that are required for the overall growth and physiological development of plants that are found in nature and that

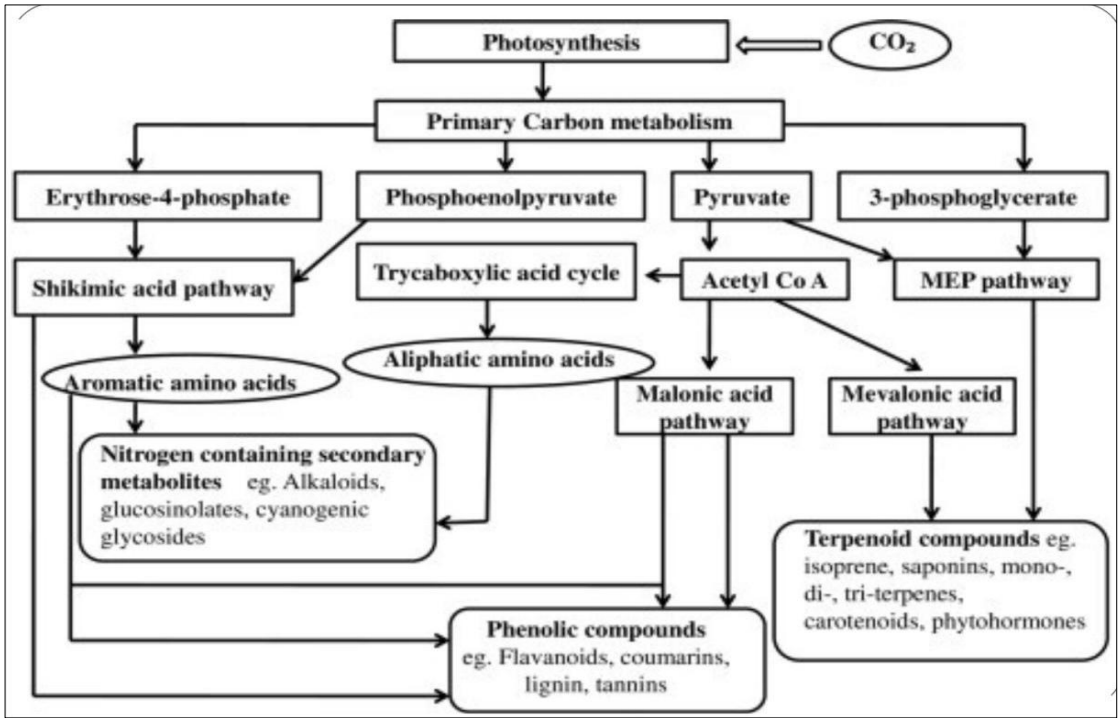
humans also eat. Alkaloids, glycosides, flavonoids, volatile oils, and other secondary metabolites are produced biosynthetically from primary metabolites. Common organic reactions such as catalysis, phosphorylation, hydride transfer, oxidation, elimination, acylation, alkylation, reduction, condensation, rearrangement, etc. are replicated in biosynthetic reactions. Though the organisms are very much different in their characteristic but in general the pathway for the production of fat, carbohydrate, protein, nucleic acid is very much similar. These common pathways in all organisms are collectively called as primary metabolism and the compound formed by these are known as primary metabolite [3].

Metabolism and Metabolic Pathways

Cell Metabolism is the process by which living cell process nutrient molecules and living state. A complete set of chemical reactions that occur in living cells, allowing cells to grow and reproduce, maintain their structures, and respond to their environments. Living cell require energy for biosynthesis, transport of nutrient, motility and maintenance. Energy is obtained from the catabolism of carbon compounds (Carbohydrate). In the presence of light, photosynthesis converts CO2 and H2O into carbohydrates. The metabolic processes that break down a substrate into smaller, simpler products are known as catabolism. generate energy for the cell. Anabolism: Metabolic processes that produce bigger, more intricate molecules. Energy is needed. Glycogen from glucose [4].

Photosynthesis

A chemical process that occurs in plant, algae, and some type of bacteria, when they are exposed to sunlight.

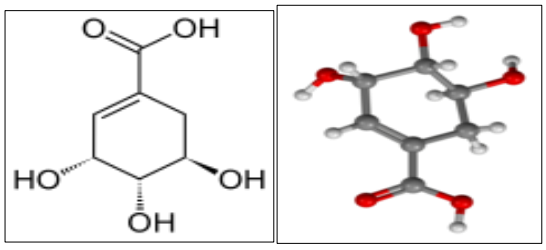


Biosynthetic Pathway of Secondary Metabolites

It involves 3 basic mechanisms:

1. Shikimic acid Pathways
2. Acetate Mevalonate Pathway
3. Acetate Melonate Pathway

[I] Shikimic acid Pathway



These three compounds-cyclohexane, cyclitol, and cyclohexane carboxylic acid-are frequently referred to as its anionic from shikimate. The Japanese stor anise, Illiciumanisatum, from which it was initially isolated by Johan Fredrik Eykman in 1885, is the source of its name. Its structure was clarified about fifty years later. Some hydrolyzable tannins also contain shikimic acid as a glycoside component [5].

Shikimic Acid Pathway

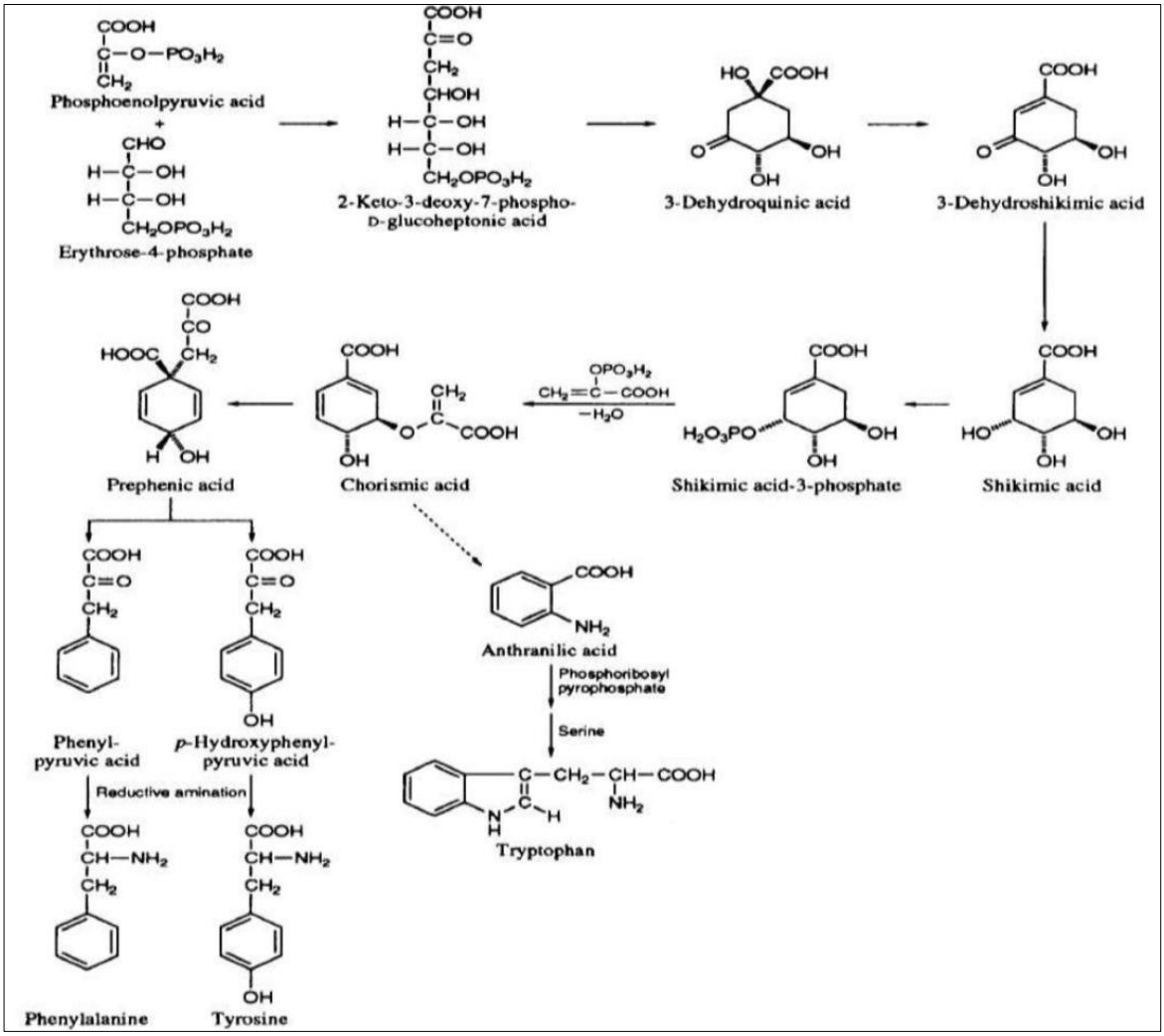
The chorismate pathway is another name for the shikimate biosynthesis pathway. The fundamental mechanism for the production of phenolic chemicals is the shikimic acid pathway, also known as the shikimikate pathway. It has the precursors of phenylpropanoid and occurs in chloroplast plant cells. The expression of phenolics is activated by environmental stressors, including pathogen and herbivore attacks, improper pH and temperature, UV radiation, salt stress, and heavy metal stress. These aromatic chemicals are a form of secondary metabolites that are prevalent in plants. Phenolics are essential for defense mechanisms, signaling agents in plant and animal communication, pigment molecules, electron transport, and antioxidants. A crucial step in the production of C6-C3 units (a derivative of phenyl propane) is the shikimic acid pathway, which starts with carbohydrates. Simple carbohydrate precursors from the pentose phosphate route and glycolysis are transformed into aromatic amino acids via the shikimic acid pathway. Bacteria, fungi, algae, parasites, and plants all use the seven-step shikimate pathway to biosynthesize aromatic amino acids like

phenylalanine, tyrosine, and tryptophane [6]. Since animals lack this process, phenylalanine and tryptophan are considered essential amino acids that must be consumed by the animal.With the exception of those who are unable to hydroxylate phenylalanine to tyrosine, animals are able to manufacture tyrosine from phenylalanine, making it a necessary amino acid.

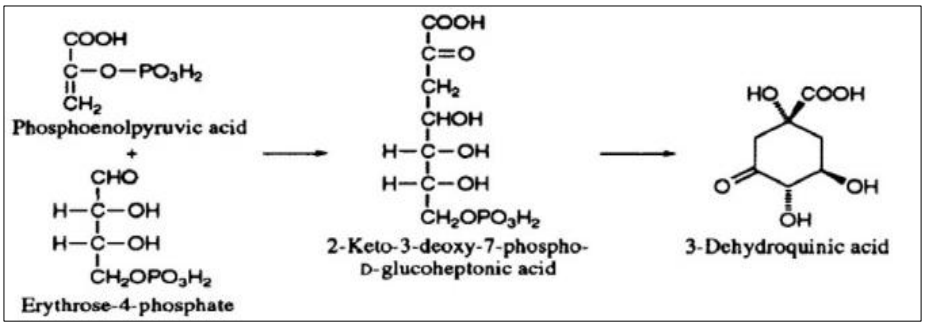
The enzymes DAHP Synthase, 3 dehydroquinate dehydrates, Shikimate dehydrogenase, Shikimate kinase, EPSP Synthase, and Chorismate synthase are all involved in the shikimate pathway.

Biosynthetic Precursor

Phosphoenol pyruvate, Erythrose 4 Phosphate, Nitrogen from other amino acid - Glutamate, Glycine, Serine.



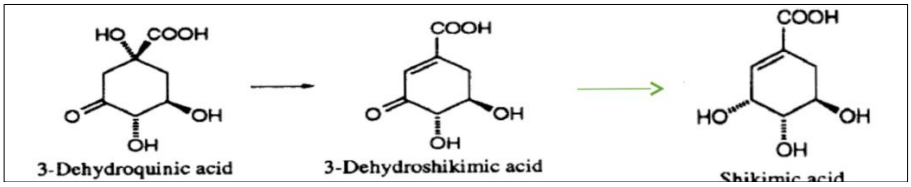
The enzyme DAHP Synthase catalyzes the reaction between phosphoenol pyruvate and erythrose 4 phosphate, forming 2 keto 3 deoxy 7 phosphoglucoheptonic acid. DHQ synthase then catalyzes the conversion of 2-keto 3 deoxy 7 phosphoglucoheptonic acid to 3 dehydroquinate (DHQ). The enzymatic process regenerates nicotine amide adenine dinucleotide (NAD), which means that no NAD is used in this reaction even though it needs it as a cofactor.



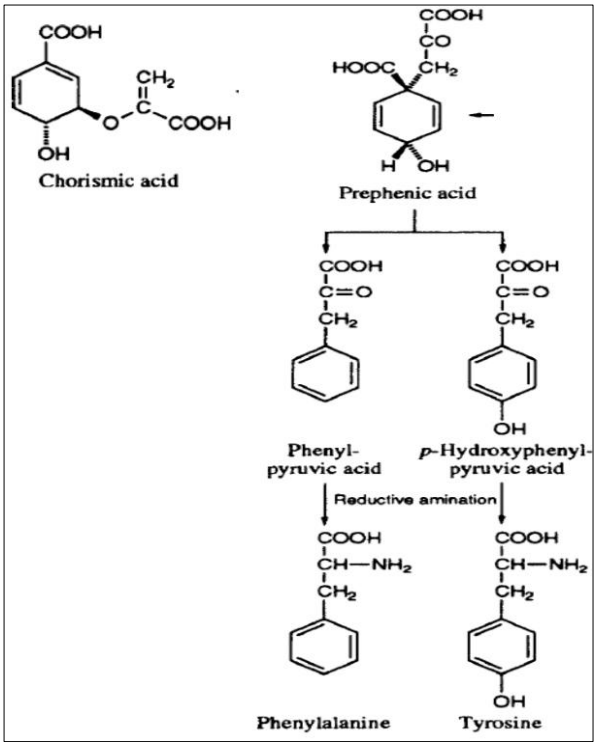
Using nicotine amide adenine dinucleotide phosphate (NADPH) as a cofactor, the enzyme 3-dehydroquinate dehydratase dehydrates DHQ to 3-dehydroshikimic acid, which is then reduced to shikimic acid by the enzyme shikimate dehydrogenase.

The next enzyme in question is shikimate kinase, which catalyzes the formation of shikimate 3-phosphate by phosphorylating shikimate in an ATP-dependent manner. The enzyme 5-enolpyruvylshikimate-3-phosphate (EPSP) synthase then combines shikimate 3-phosphate with

phosphoenol pyruvate to produce 5-enolpyruvylshikimate-3-phosphate. A chorismate synthase then converts 5-enolpyruvylshikimate-3-phosphate to chorismate.



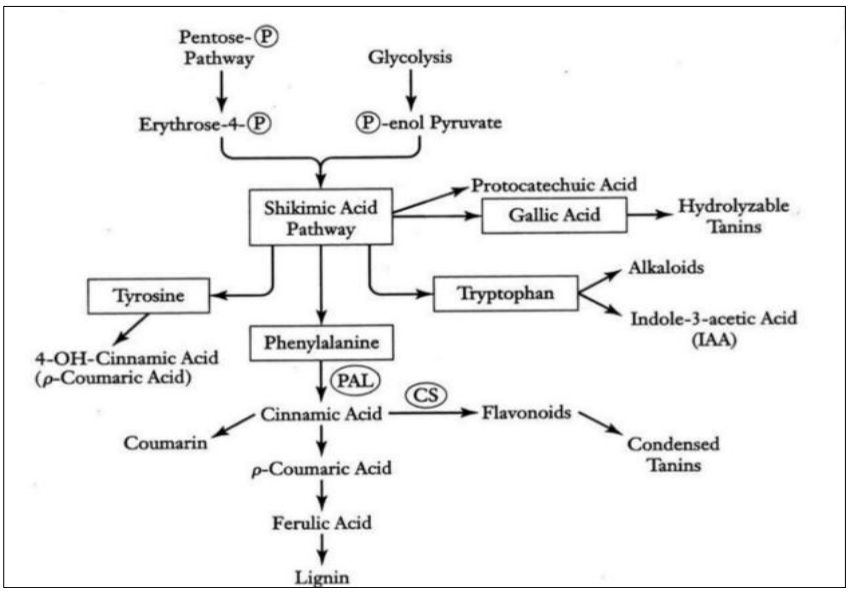
Chorismatemutase then uses a Claisen rearrangement of chorismate to create prephenic acid.

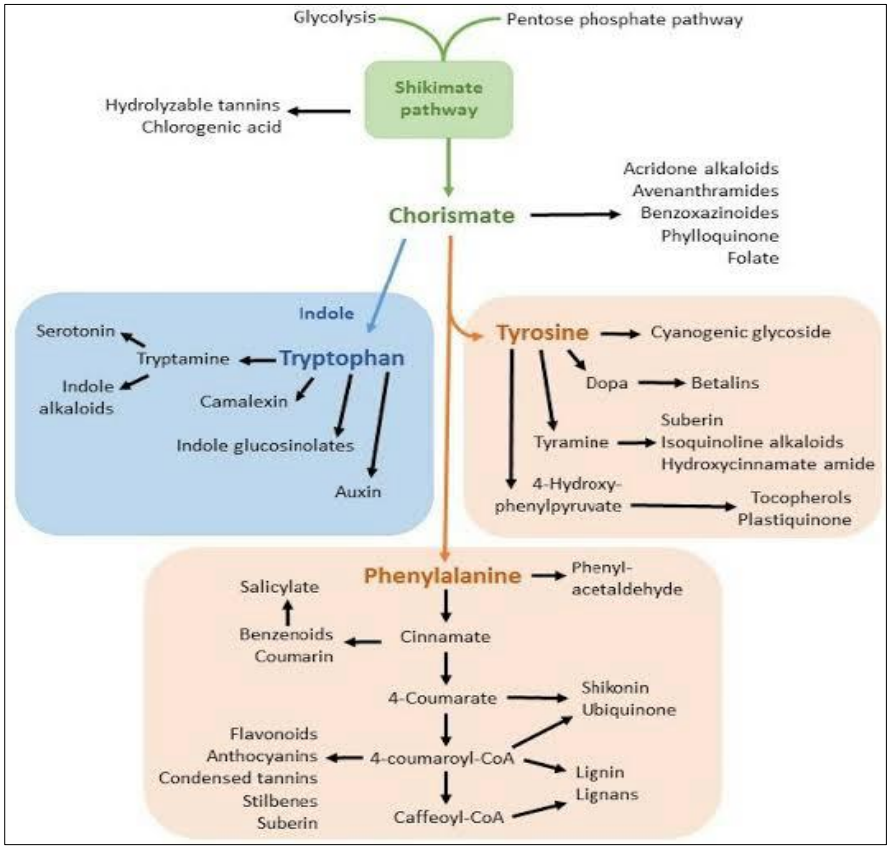


Tyrosine and α-ketoglutarate are produced when prephenate dehydrogenase oxidatively decarboxylates prephenate while retaining the hydroxyl group. This results in hydroxy phenyl pyruvate, which is then transaminated with glutamate as the nitrogen supply. Prephenate dehydratase catalyzes the aromatization of prephanic acid to phenyl pyruvic acid, which is the initial step in the biosynthesis of phenylalanine. Phenylalanine aminotransferase subsequently catalyzes the transamination process, which yields phenylalanine [7].

Pathway

Beginning Point for Some Phenolics' Biosynthesis The building blocks for the production of phenyl propanoids are tyrosine and phenyl alanine.





Role of shikimic acid Pathway

Beginning with the phenolics' biosynthesis: The precursors for the production of phenyl propanoids include tyrosine and phenyl alanine. The flavonoids lignins, tannins, and coumarins are subsequently made from the phenyl propanoids. Biosynthesis of galic acid The enzyme shikimate dehydrogenase converted 3 dehydro shikimate into 3,5 di dehydro shikimate, which is then converted into galic acid. The later compound spontaneously rearranges to gallic acid. Other compounds Shikimic acid is a precursor for: Indole, indole derivatives and aromatic amino acid tryptophan and tryptophan derivatives such as the psychedelic compound dimethyl tryptamine and many alkaloids and other aromatic metabolites [8].

Important Derivatives

Phenylpropanoids: Discuss the biosynthesis and therapeutic properties of flavonoids (antioxidant, anti-inflammatory), tannins, and lignin. Alkaloids: Explain the derivation of indole alkaloids, such as vincristine and vinblastine (anticancer agents), from tryptophan. Other Metabolites: Cover other notable compounds like salicylic acid (a precursor to aspirin) and shikimic acid itself (used to produce the antiviral agent oseltamivir).

Uses

The Chinese star anise (Illicium verum) yields shikimic acid, which is utilized in the pharmaceutical sector as a basis material to produce oseltamivir (Tamiflu). Drug target: (6S)-6-Fluoroshikimic acid, an antibiotic that blocks the aromatic biosynthesis pathway, can be made from shikimate. The herbicid Roundup's primary ingredient, glyphosphate, kills plants by disrupting their shikimate pathway. More precisely, 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS) is inhibited by glyphosate. Genetically modified crops that are "Roundup Ready" get past that restriction.

Target for Drugs

Shikimate can be utilized to create the antibiotic (6S) 6-fluroshikimic acid, which blocks the aromatic biosynthesis pathway. The herbicide Roundup's primary ingredient, glyphosate, kills plants by disrupting their shikimic pathway. The enzyme 5 enol pyruvyl shikimate 3 phosphate synthases (EPSPS) is selectively inhibited by glyphosate. [9].

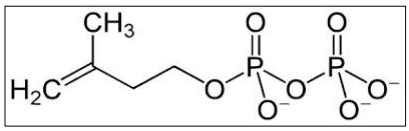
[II] Acetate - Mevalonate Pathway

Acetate mevalonate pathway: Terpenoids and steroids are biosynthesized by the acetate mevalonate pathway. The biogenesis of these compounds follows the 'Isoprene Buie according to which they are built up from isoprene units joined by a head to tail linkages. The Mevalonate acid pathway is the core of metabolic pathway for multiple cellular metabolisms in eukaryotic, archaea, and some bacteria organisms, including cholesterol biosynthesis and protein prenylation. Cholesterol is produced as the molecules that used to build the membrane cell structure, steroid hormones, myelin sheets in neurone system, precursors of vitamin D, formation and release of synaptic vesicles.

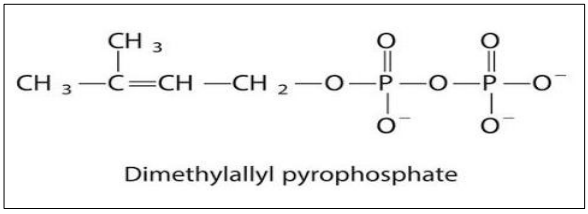
The primary precursor is mevalonic acid, which in turn is derived from acetyl CoA through the intermediate formation of acetoacetyl CoA and 3 hydroxy 3 methyl glutaryl CoA. The main difference between the acetate malonate and this pathway is the addition of the third acetate unit to aceto acetyl CoA. In the former pathway, as shown earlier, the linkage is in a linear fashion, while in the latter pathway, the third acetate molecules are added to the central carbonyl function to yield a branched six carbon unit, viz., 3 hydroxy 3 methyl glutaryl CoA. The subsequent reduction of gives mevalonic acid which serves as the precursor for various terpenoidal and steroidal molecules us shown.

The mevalonate pathway also known as the isoprenoid pathway or HMG CoA reductase pathway is an essential metabolic pathway present in eukaryotes, archaea, and some bacteria. The pathway produces two five carbon building

blocks called isopentyl pyrophosphate (IPP) and dimethylallyl pyrophosphate (DMAPP), which are used to make isoprenoids, a diverse class of over 30,000 biomolecules such as cholesterol, heam, vitamin K, Coenzyme Q and all steroid hormones. The mevalonate pathway begins with acetyl CoA and ends with the production of IPP and DMAPP. It is best known as the target of stains, a class of cholesterol lowering drugs. Stains inhibit HMG CoA reductase within the mevalonate pathway [10].



Isopentyl pyrophosphate



Monoterpenes (C10): Found in essential oils (e.g., menthol in mint, limeonene in citrus). Sesquiterpenes (C15): Including the antimalarial drug artemisinin. Diterpenes (C20): Such as gibberellins (Plant hormones) and paclitaxel (Taxol), a potent anticancer agent. Triterpenes (C30): Like steroids and saponins.

Types of Mevalonate pathway

There are two types:

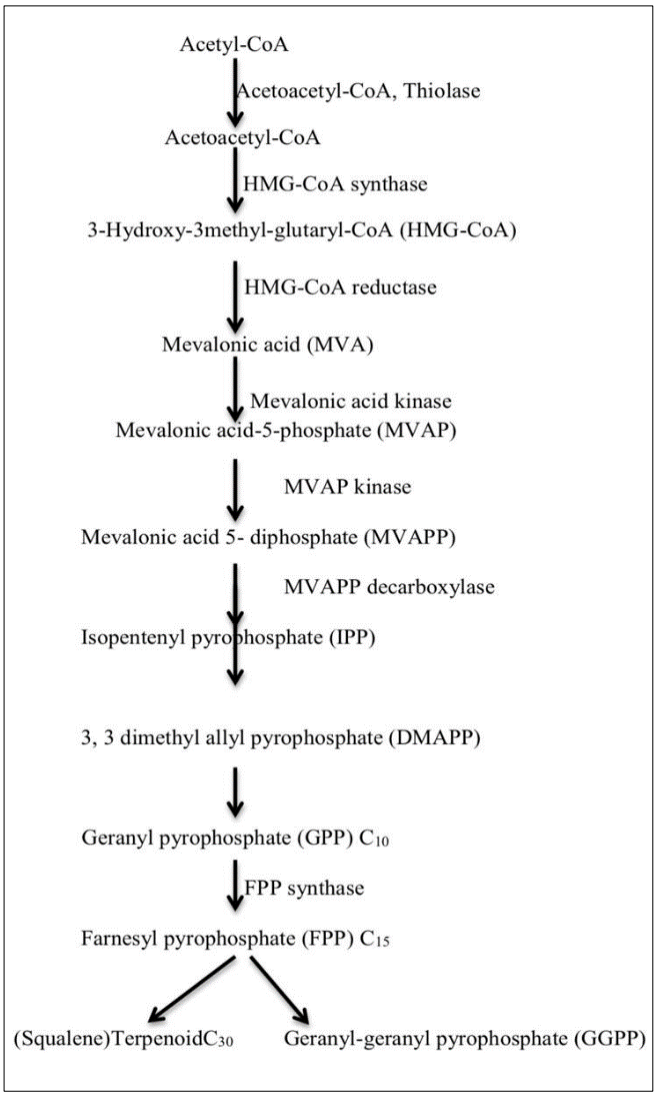
1. Upper Mevalonate Pathway
2. Lower Mevalonate Pathway

Upper Mevalonate Pathway

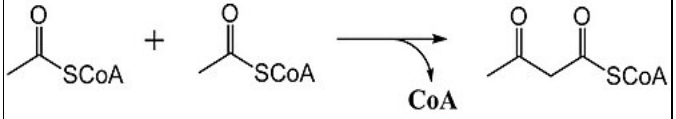
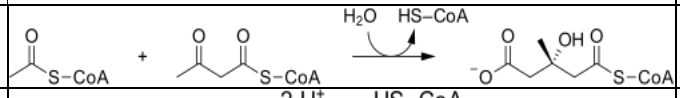
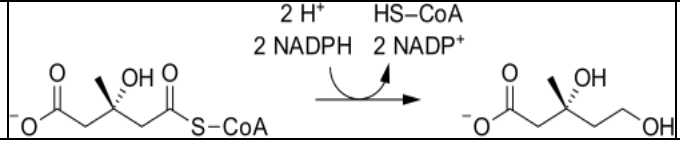
The mevalonate pathway of eukaryotes, archaea, and eubacteria all benign the same way. The sole carbon feed of the pathway is acetyl CoA. The first step condenses two acetyl CoA molecules to yield aceto acetyl CoA. This is followed by a seconed condensation to form HMG CoA (3 hydroxy 3 methyl glutaryl CoA). Reduction of HMG CoA yields mevalonate. This first 3 enzymatic steps are called as the upper mevalonate pathway.

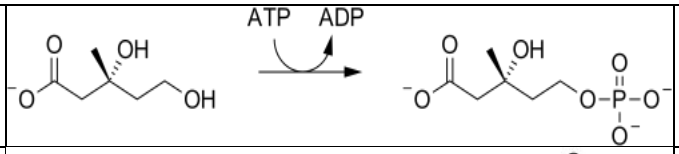
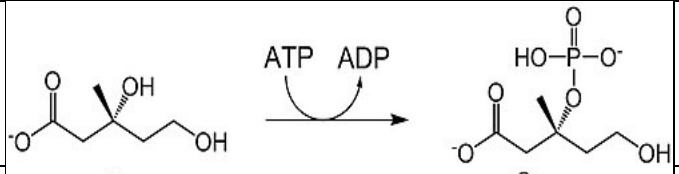
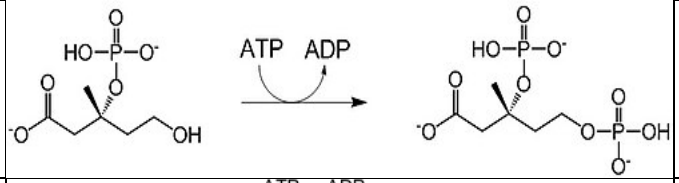
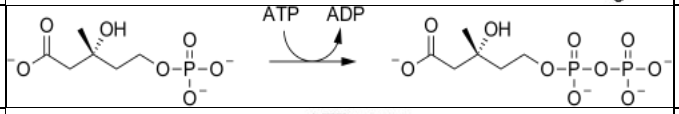
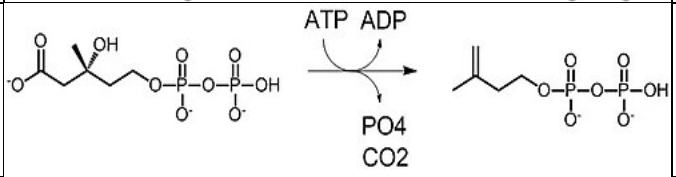
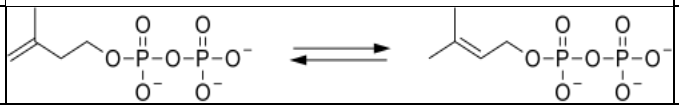
Lower mevalonate Pathway

The lower mevalonate pathway which converts (R)-mevalonate into IPP and DMAPP has 3variants. In eukaryotes, mevalonate is phosphorylated twice in the 5-OH position, then decarboxylated to yield IPP. In some archaea such as *Haloferax volcanii*, mevalonate is phosphorylated once in the 5-OH position, decarboxylated to yield isopentenyl phosphate (IP') and finally phosphorylated again to yield IPP (Archaeal Mevalonate Pathway l). A third mevalonate pathway variant found in *Thermoplasma acidophilus*, phosphorylates mevalonate at the 3-OH position followed by phosphorylation at the S-OH position. The resulting metabolite, mevalonate-3,5-bisphosphate, is decarboxylated to IP, and finally phosphorylated to yield IPP (Archaeal Mevalonate Pathway II) [11].



Enzymatic reactions [12]

Enzyme	Reaction	Description
Acetoacetyl-CoA thiolase		The citric acid cycle's acetyl-CoA condenses with another acetyl-CoA molecule to create acetoacetyl-CoA.
HMG-CoA synthase		3-hydroxy-3-methylglutaryl-CoA (HMG-CoA) is created when acetoacetyl-CoA condenses with another acetyl-CoA molecule.
HMG-CoA reductase		NADPH reduces HMG-CoA to mevalonate. This enzyme is a good target for medications (statins) since it is the rate-limiting step in the synthesis of cholesterol.

mevalonate-5-kinase		To create mevalonate-5-phosphate, commonly known as phosphomevalonic acid, mevalonate undergoes phosphorylation at the 5-OH position.
mevalonate-3-kinase		Mevalonate-3-phosphate is produced when mevalonate is phosphorylated at the 3-OH site. One ATP is used up.
mevalonate-3-phosphate-5-kinase		Mevalonate-5-phosphate, commonly known as phosphomevalonic acid, is produced when mevalonate-3-phosphate is phosphorylated at the 5-OH position. One ATP is used up.
phosphomevalonate kinase		Mevalonate-5-pyrophosphate is produced by phosphorylating mevalonate-5-phosphate. One ATP is used up.
mevalonate-5-pyrophosphate decarboxylase		Isopentenyl pyrophosphate (IPP) is produced by decarboxylating mevalonate-5-pyrophosphate. One ATP is used up.
isopentenyl pyrophosphate isomerase		Dimethylallyl pyrophosphate is the isomer of isopentenyl pyrophosphate.

Importance Derivatives

Terpenoids: Categorize terpenoids (monoterpenes, Diterpenes, sesquiterpenes) and provide examples with medicinal uses. Anticancer agents: Paclitaxel (Diterpenoid) and Cucurbitacin's (tetracyclic triterpene). Antimalarials: Artemisinin (sesquiterpene lactone). Anti inflammatory and antioxidant agents: Many essential oil components. Steroids: Sterols (e.g., Cholesterol) and steroid hormones derived from the pathway.[13]

Applications in pharmacognosy

Combinatorial Biosynthesis: Explain how manipulating PKS modules can generate novel polyketide structure with unique pharmacological properties. Host vactor systems: Describe the development of host vector systems for producing novel polyketides in engineered microorganisms.

[III] Acetate Malonate Pathway

The polyketide route is another name for this mechanism. Fatty acids and aromatic chemicals are synthesized via the acetate malonate route with the aid of secondary metabolites. Acetyl CoA and Malonyl CoA are the primary precursors of the Acetate Malonate Pathway. Polyketides or saturated or unsaturated fatty acids may be the end result of this process. The Polyketide Pathway uses polyketides, which are secondary metabolites, to further manufacture aromatic chemicals. The acyl carrier protein (ACP) is involved in the acetate process, which produces fatty acyl thioesters of ACP. The crucial steps in the production of fatty acids are formed by these acyl thioesters. These C2 acetyl CoA units eventually generate an even number of fatty acids, ranging from n-ecosanoic (arachidic acid) to n-tetranoic (butyric). Thus, the following reactions describe the production of fatty acids. Subsequent direct dehydrogenation of saturated fatty acids yields unsaturated fatty acids. The location of recently added double bonds in fatty acids is mostly controlled by enzymes. Green tissues' chloroplasts and non-photosynthetic tissues' plastids biosynthesize fatty acids, which are made up of an aliphatic carbon chain with a carboxylic acid group at one end and a methyl group at the other [14].

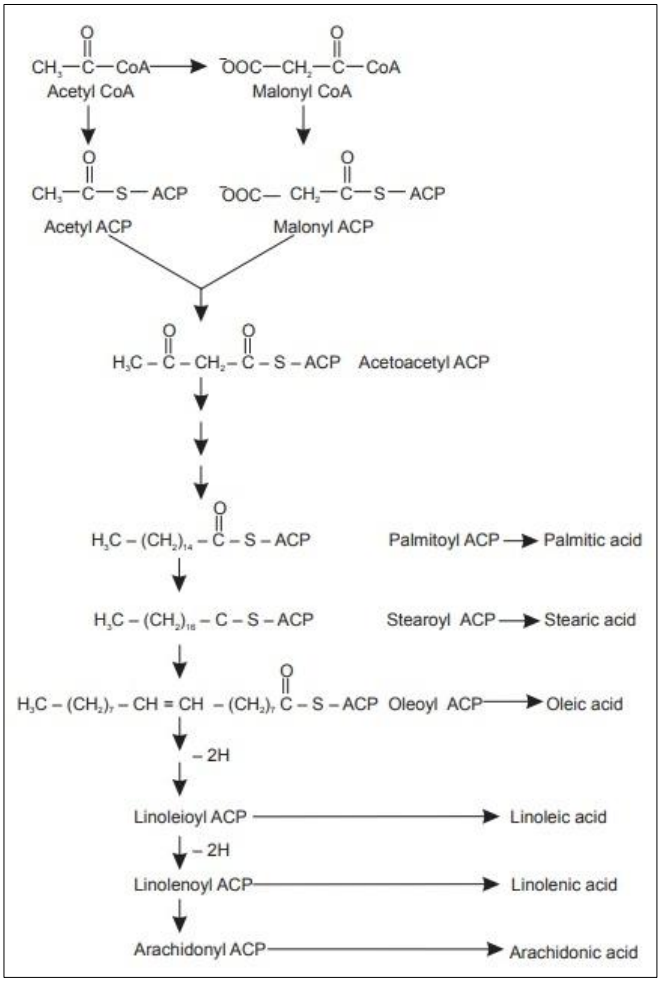
Fatty acid production depends on two enzyme systems: fatty acid synthase and acetyl-CoA carboxylase. In mitochondria, lipoic acid is biosynthesised. The various saturated, unsaturated, and very long chain fatty acids are then converted into triacylglycerols, waxes, lipid polyesters (cutin, suberin), sphingolipids, or oxylipins. Membranes, cell walls, storage molecules, and signaling molecules all contain various kinds of these lipids. Most polyketides are aromatic derivatives, and their biogenesis processes distinguish them from one another. Three different types of polyketide synthases-type I, type II, and type III-are the enzymes that comprise the polyketide backbone. Type I PKS: Large, modular, multi-domain proteins involved in synthesizing complex macrocycles like macrolides. Type II PKS: Composed of separate, dissociable protein subunits, typically leading to aromatic polyketides. Type III PKS (chalcone synthases): Found in plants, these enzymes act more simply and are involved in flavonoid synthesis [15].

Polyketides are often categorized into two types. Aflatoxin, usnic acid, 6-methylsalicylic acid, anthraquinones, flavonoids, stilbenes, curcuminoids, coniine-related alkaloids, and other complex and aromatic polyketides are among them [16].

Polyketides

This large and diverse class of secondary metabolites is a cornerstone of natural product drug discovery. Flavonoids: These compounds, widely known for their antioxidant, anti-inflammatory, and cardio protective effects, are formed by the cyclization of polyketide intermediates. Anthraquinones: Used as natural laxatives, these aromatic polyketides are found in plants like senna and cascara. Antibiotics: Many clinically vital antibiotics, such as erythromycin (a macrolide)

and tetracycline, are polyketide products derived primarily from microorganisms [17]. Other aromatic compounds: The pathway is also responsible for stilbenes (like resveratrol) and curcuminoids (from turmeric), both of which have been studied for their potential therapeutic benefits [18].



Important Derivatives

Antibiotic: Discuss major polyketide-derived antibiotics, such as erythromycins and tetracyclines. Immuno suppressants: Mention compounds like rapamycin and tacrolimus (FK506) [19]. Fatty Acids and Lipids: Cover pharmaceutically relevant fatty acids like ricinoleic acid (from castor oil) and unique examples like the cyclo propene fatty acid sterculic acid [20].

Applications in Pharmacognosy

Biosynthetic Studies: Detail the use of stable isotope labeling to elucidate the steps of complex polyketide biosynthesis. Metabolic Engineering: Discuss altering polyketide production by modifying starter and extender units or by engineering PKS system [21]. Combinatorial biosynthesis: Manipulating PKS genes to create novel polyketides. Module swapping: Recombining PKS genes to generate new chemical structures. Engineered microorganisms: Using bacteria or yeast as "factories" for polyketide production [22].

References

1. Alberts B. Molecular Biology of the Cell. 5th ed. New York: Garland Science; 2008. ISBN 9780815341055. p. 1-1463.
2. Cox DL, Nelson MM. Lehninger Principles of Biochemistry. 5th ed. New York: W.H. Freeman; 2008. ISBN 9780716771081. p. 1-1119.
3. Prabhu K, Arunachalam G. Pharmacognosy and Phytochemistry-II. e-Book for B.Pharm 5th Semester. PharmaMed Press; 2019. p. 1-250.
4. Birolo L, Arnone MI, Cubellis MV, Andreotti G, Nitti G, Marino G, Sannia G. The active site of *Sulfolobus solfataricus* aspartate aminotransferase. Biochim Biophys Acta. 1991;1080(3):198-204.
5. Enrich LB, Scheuermann ML, Mohadjer A, Matthias KR, Eller CF, Newman MS, Fujinaka M, Poon T. *Liquidambar styraciflua*: a renewable source of shikimic acid. Tetrahedron Lett. 2008 Apr;49(16):2503-2505.
6. Rawat G, Tripathi P, Jahan F, Saxena RK. A natural isolate producing shikimic acid: isolation, identification, and culture condition optimization. Appl Biochem Biotechnol. 2013;169(8):2290-2302.
7. Herrmann KM, Weaver LM. The shikimate pathway. Annu Rev Plant Physiol Plant Mol Biol. 1999;50(1):473-503.
8. Quiroz DCD, Carmona SB, Bolívar F, Escalante AA. Current perspectives on applications of shikimic and amino shikimic acids in pharmaceutical chemistry. Res Rep Med Chem. 2014;4:35-46.
9. Batory M, Rotsztejn H. Shikimic acid in the light of current knowledge. J Cosmet Dermatol. 2022;21(2):501-505.
10. Goldstein JL, Brown MS. Regulation of the mevalonate pathway. Nature. 1990;343(6257):425-430.
11. Vinokur JM, Korman TP, Cao Z, Bowie JU. Evidence of a novel mevalonate pathway in archaea. Biochemistry. 2014;53(25):4161-4168.
12. Vickery ML, Vickery B. Secondary Plant Metabolism. London: Macmillan; 1981. p. 56-110.
13. Talapatra SK, Talapatra B. *Chemistry of Plant Natural Products.* Berlin: Springer-Verlag; 2015. p. 1-900.
14. Khadabadi SS, Deore SL, Baviskar BA. Pharmacognosy and Phytochemistry: A Comprehensive Approach. 1st ed. Hyderabad: PharmaMed Press; 2014. p. 1-350.
15. Goldstein JL, Brown SB. Regulation of the mevalonate pathway. Nature. 1990;343(6257):425-430.
16. Hertweck C. The biosynthesis of polyketides: a comparative perspective. Acc Chem Res. 2009;42(10):1603-1611.
17. Dewick PM. The Biosynthesis of Natural Products. Chichester: John Wiley & Sons; 2002. p. 1-550.
18. Hertweck C. The biosynthesis of polyketides: a comparative perspective. Acc Chem Res. 2009;42(10):1603-1611.
19. Kokate CK, Purohit AP, Gokhale SB. Pharmacognosy. 20th ed. Pune: Nirali Prakashan; 2002. p. 1-624.
20. Xia Y, Zhang Y, Zhang Y, Liu Y, *et al*. The mevalonate pathway is a druggable target for vaccine adjuvant discovery. Cell. 2018;175(4):1059-1073.e21. doi:10.1016/j.cell.2018.08.070.
21. Sanchez NF, Coronado RS, Carlos BH, Villanueva C. Shikimic acid pathway in biosynthesis of phenolic compounds. Plant Physiol Asp Phenolic Compd. 2018;32:137-144.
22. Dandu G, Basu VR, Kamalakar K, Manasa CH, Lavanya B, Pavani J. A review on tracer technique and its applications in synthesis of secondary metabolites in pharmacognosy. Int J Adv Pharm Biotech. 2019;5(1):1-5.