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The Biochemistry Behind Natural Secondary Metabolites and Their Significance

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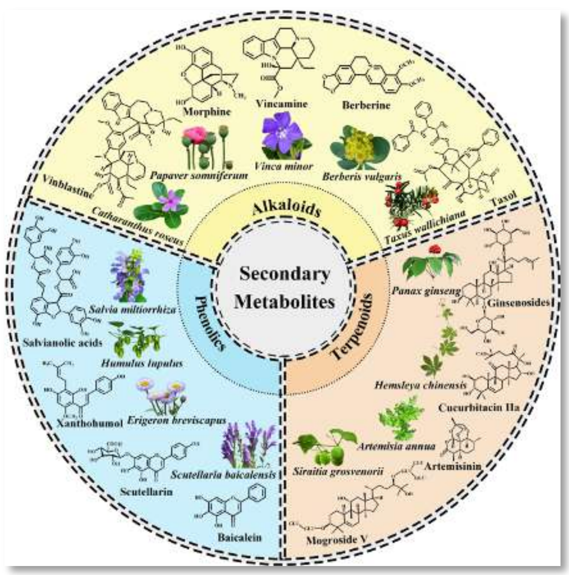
Priya Pandey[1], R.N. Kewat[2], Sheetanu Singh[1], Garima Dixit[3]

[1]Research Scholar, Department of Biochemistry, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya

[2]Professor, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya

[3]Research Scholar, Department of Food and Nutrition, Acharya Narendra Deva University of Agriculture and Technology, Kumarganj, Ayodhya

Natural products are chemical compounds derived from living organisms, and their study involves understanding their biosynthesis, extraction, identification, quantification, and chemical characteristics. These compounds arise from primary or secondary metabolic processes—complex enzymatic reactions within cells that support growth, development, and environmental adaptation. While primary metabolites such as carbohydrates, proteins, and fats are essential for plant growth and reproduction, secondary metabolites do not directly contribute to these functions but play vital roles in plant interaction with their surroundings. These secondary metabolites, which include alkaloids, tannins, flavonoids, and phenolic compounds, are often localized in specific plant parts such as leaves, roots, stems, or bark, and tend to be unique to particular species or groups. Once thought to be mere metabolic byproducts, secondary metabolites are now recognized for their distinct structures and significant ecological functions. They protect plants against biological threats like pathogens and herbivores, as well as abiotic stresses including drought, temperature extremes, and heavy metals. Moreover, they contribute to the coloration of flowers and seeds, facilitating pollination and seed dispersal, thus supporting plant reproduction. Beyond their ecological roles, many secondary metabolites are utilized commercially as natural aromas, resins, flavoring agents, insecticides, and herbicides. Importantly, their diverse pharmacological properties have made them



invaluable in pharmaceutical research and drug development. This article reviews the major classes of plant secondary metabolites, common extraction and phytochemical analysis techniques, and emphasizes their key pharmacological activities.

Classes of Secondary Metabolites in Plants

Plant secondary metabolites (SMs) are commonly classified based on factors like chemical structure, composition, solubility, and biosynthetic pathways. Among these, the biosynthetic pathway is the most widely used criterion, dividing SMs into three main groups: terpenes, phenolic compounds, and alkaloids.

Terpene: Terpenes represent the largest class of plant secondary metabolites, with over 40,000 known compounds. They are non-saponifiable lipids, meaning they do not involve fatty acids in their synthesis. Also referred to as isoprenoids, terpenes are built from isoprene units and classified by the number they contain. Hemiterpenes have one unit, while others include monoterpenes (2 units), sesquiterpenes (3), diterpenes (4), triterpenes (6), tetraterpenes (8), and polyterpenes (10 or more). Found in many aromatic plants such as lemon, mint, and basil, these compounds contribute to plant scents. Terpenes play roles in both primary metabolism—as pigments, electron carriers, membrane components, and growth regulators—and in secondary metabolism as defense compounds, insect deterrents, and attractants for pollinators. They are synthesized via two main pathways: the mevalonic acid (MVA) pathway in the cytosol and the methylerythritol phosphate (MEP) pathway in chloroplasts, both producing isopentenyl diphosphate (IPP) as a key intermediate.

Phenolic Compounds: Phenolic compounds are a broad group of plant secondary metabolites that feature a hydroxyl group bonded to an aromatic ring. They vary widely in structure, with phenol being the simplest form. Based on carbon content, phenolics are classified into types such as simple phenols, flavonoids, coumarins, tannins, quinones, xanthones, and others. Some, like lignans and tannins, are larger polymers with complex structures. These compounds are synthesized in plants via the shikimic acid pathway, malonate/acetate pathway, or both. The shikimic pathway produces amino acids and derivatives like phenylpropanoids and coumarins, while the polyacetate pathway gives rise to compounds like quinones. Flavonoids typically originate from both pathways. Phenolic compounds serve many purposes: they act as antioxidants, inhibit seed germination, absorb UV radiation, and give fruits their color and scent to attract animals for seed dispersal. They also play roles in plant competition (allelopathy) and defense, by forming toxic phytoalexins or producing bitter tastes that deter herbivores.

Alkaloids: Alkaloids are a large and varied group of nitrogen-containing secondary metabolites, primarily found in vascular plants, but also present in fungi, bacteria, and animals. Each plant typically produces a complex mix of alkaloids, often dominated by one main type. Their concentration can vary between different plant parts. Alkaloids are usually toxic, reactive, and can be identified by common precipitation reactions.

They are commonly classified based on their biosynthetic origin into:

- **True Alkaloids**: Derived from amino acids, contain nitrogen within a heterocyclic ring, and are the most common type.
- **Protoalkaloids**: Also amino acid-derived, but nitrogen is located outside the ring structure.
- **Pseudoalkaloids**: Contain nitrogen in a ring but are not amino acid-derived; nitrogen is added later, such as in terpenoid alkaloids.

These compounds often occur as salts in plants and perform various biological functions, including defense.

Bioactivity – Antimicrobial Activity

The growing prevalence of antibiotic resistance in microorganisms has become a significant concern for the global scientific community. Many herbal preparations used in traditional medicine by indigenous cultures worldwide are known to possess antimicrobial properties. This traditional knowledge has inspired modern research focused on discovering plant-based compounds with antibacterial and antifungal potential for pharmaceutical development.

Terpenes: Terpenes extracted from plant bark have shown antibacterial effects against *S. faecalis*, MRSA, and *P. aeruginosa*. Ethanol extracts of *Morinda citrifolia* leaves, rich in terpenoids, are effective against *P. aeruginosa* and *S. epidermidis*. Studies on plant families such as Asteraceae, Lamiaceae, and Rutaceae also highlight strong antimicrobial activity of terpenes. While terpenoids play a major role, other phytochemicals may also contribute to the observed antimicrobial effects.

Phenolic Compounds: Many naturally occurring phenolic compounds exhibit antimicrobial properties that help protect plants from phytopathogens. For example, studies on secondary metabolites extracted from grapes and almond plants have shown antibacterial activity against gram-negative bacteria like *Xylella fastidiosa*.

Alkaloids: Alkaloids have been used for centuries as active ingredients in traditional herbal remedies, though some are also known for their abuse potential and toxicity to humans due to their cytotoxic effects. Various Middle Eastern plants, including *Datura stramonium*, *Peganum harmala*, and *Achillea millefolium*, have been widely studied. Denatured alkaloids extracted from these species have shown effectiveness against several pathogens, including *E. coli*, *S. aureus*, *P. aeruginosa*, *K. pneumoniae*, and *Proteus mirabilis*.

Therapeutic Potential of Plant Secondary Metabolites in Modern Medicine

Phytochemicals are widely utilized as sources for plant-derived drugs and have been a key component of traditional and folk medicine for centuries. In modern medicine, they are valued for their antimicrobial, antioxidant, and anti-diabetic properties [36]. Advances in genetic engineering and bioinformatics have made it possible to identify, analyze, and mass-produce novel secondary metabolites with pharmaceutical potential. Contemporary extraction methods are more efficient in terms of time and energy and require less raw material. Additionally, recombinant DNA (rDNA) technology is employed to minimize toxicity and enhance the consistency and reliability of the desired bioactive compounds.

Anti-Cancer Potential of Plant Secondary Metabolites

Cancer is a complex, multi-stage disease characterized by uncontrolled cell growth that leads to the formation of malignant tissue. While synthetic chemotherapy drugs often damage healthy cells, there is increasing interest in naturally derived anti-cancer compounds. Various plant secondary metabolites—including alkaloids, diterpenes, triterpenes, and polyphenols—have demonstrated significant potential as anti-cancer agents in recent research. Studies indicate that some of these compounds exhibit cytotoxic effects specifically targeting cancerous cells. However, many promising metabolites face challenges in clinical use due to poor bioavailability. Additionally, some plant-derived compounds can be toxic to normal human cells but show strong anti-tumor activity. By chemically modifying these metabolites to reduce their toxicity, they may become viable options for cancer treatment. Curcumin, a lipophilic phenolic substance with an orange-yellow crystalline appearance, is extracted from turmeric (*Curcuma longa* L.). Turmeric rhizomes contain 2-5% curcumin and have long been used in traditional Chinese and Indian medicine. The regular dietary use of turmeric is linked to health benefits such as anti-inflammatory, antioxidant, and cancer-preventive properties, possibly contributing to the low rates of gastrointestinal cancers in South Asia. Many laboratory studies demonstrate curcumin's effectiveness in cancer treatment by influencing multiple cellular pathways to induce cancer cell death, while having little harmful impact on healthy cells.

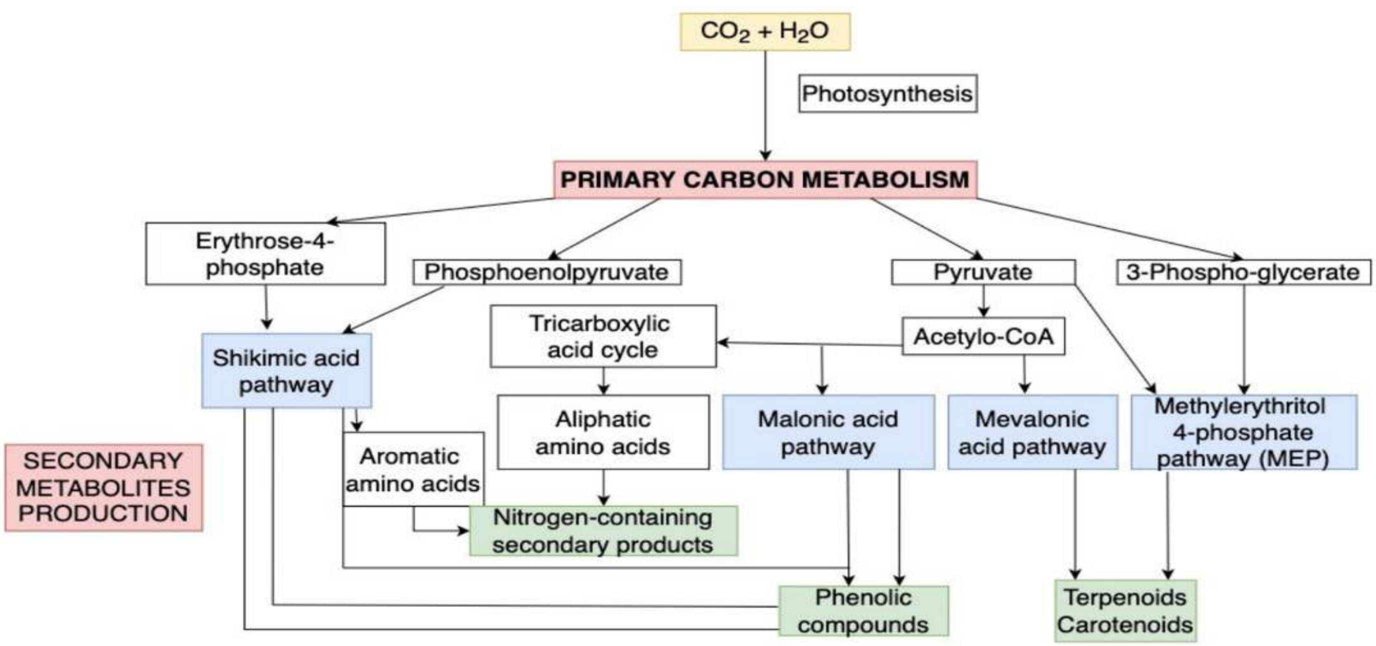


Figure-1 Main pathways for the synthesis of secondary metabolites in trees

Conclusion

Plant secondary metabolites represent a diverse group of naturally occurring compounds that, while not essential for plant growth, play crucial roles in plant defense, ecological interactions, and survival under stress. These compounds—primarily terpenes, phenolic compounds, and alkaloids—are synthesized through distinct biosynthetic pathways and are distributed variably among plant organs. Their unique structures and bioactivities have not only ecological importance but also immense pharmaceutical value. Traditionally used in herbal medicine, secondary metabolites are now central to modern drug discovery for their antimicrobial, antioxidant, and anti-cancer properties. Advances in biotechnology, including genetic engineering and rDNA technology, have significantly enhanced the extraction, analysis, and development of these compounds for therapeutic purposes. Particularly, their role in combating drug-resistant pathogens and targeting cancer cells while minimizing harm to healthy tissues highlights their potential as safe and effective alternatives to synthetic drugs. Overall, secondary metabolites bridge traditional knowledge and modern science, offering sustainable and powerful tools in the development of future medicines.

References

1. González Mera, I. F., González Falconí, D. E., & Morera Córdova, V. (2019). Secondary metabolites in plants: Main classes, phytochemical analysis and pharmacological activities. *1000 Revista Biociencias*, *4*(4), Article 11.
2. Nwokeji, P. A., Enodiana, O. I., Ezenweani, S. R., Osaro-Itota, O., & Akatah, H. A. (2016). The chemistry of natural product: Plant secondary metabolites. *International Journal of Technology Enhancements and Emerging Engineering Research*, *4*(8), 1. ISSN 2347-4289.
3. Pagare, S., Bhatia, M., Tripathi, N., Pagare, S., & Bansal, Y. K. (2015). Secondary metabolites of plants and their role: Overview. *Current Trends in Biotechnology and Pharmacy, 9*(3), 293–304.
4. Rami, E., Singh, A., & Favzulazim, S. (2021). An overview of plant secondary metabolites, their biochemistry and generic applications. *The Journal of Phytopharmacology, 10*(5), 421–428.