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## POPULAR ARTICLE

# Secondary metabolites in plant defence

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Manuscript received: September 14, 2026; Decision on manuscript, September 16, 2026; Manuscript accepted: September 22, 2026

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## Intricacies of the subject

Plants synthesize thousands of organic compounds through highly coordinated metabolic pathways. These compounds are broadly associated with two major aspects of plant metabolism. Primary metabolites are essential for basic biological processes such as growth, development, energy production and reproduction. In addition to these compounds, plants produce a diverse group of compounds known as secondary or specialized metabolites. These compounds are particularly important in interactions between plants and their environment. Metabolites are organic compounds synthesized by organisms through enzyme mediated chemical reactions that occur through metabolic pathways. Primary metabolites are generally widespread because they perform fundamental functions required by plant cells. Secondary metabolites, in contrast, are distributed more variably across the plant kingdom and often have functions that are specific to particular plants or ecological situations. Many of them are responsible for colour, fragrance and flavour and participate in interactions with other organisms.

## Introduction

Plant metabolites collectively contribute to

growth and development, energy production and storage, structural integrity, stress tolerance, defence against biotic stress, antioxidant protection, signalling and regulation, and nutritional value. They also act as precursors for the synthesis of hormones, pigments, cell wall components, and other biologically active compounds, thereby linking different physiological and developmental processes. The composition and accumulation of metabolites can vary with genotype, developmental stage, and environmental conditions, enabling plants to adjust their physiology in response to changing conditions. Thus, metabolism is not restricted to the production of compounds required for cellular growth; it also provides the chemical and structural basis for plant survival and adaptation.

## Structural metabolites

Structural metabolites are biomolecules that form the physical framework of plant cells and tissues. They provide mechanical strength, rigidity, protection and structural integrity. Unlike compounds whose major roles are chemical defence or signalling, structural metabolites are integrated into the cell wall, cuticle and supporting tissues. Their deposition changes during cell expansion, maturation and



vascular development, allowing plants to maintain cell shape and tissue organization

while responding to mechanical and environmental stresses.

**Table 1: Primary and secondary metabolites**

| Feature      | Primary metabolites                                         | Secondary metabolites                                               |
|--------------|-------------------------------------------------------------|---------------------------------------------------------------------|
| Role         | Essential for growth, development and reproduction          | Not directly involved in growth, development and reproduction       |
| Distribution | Generally widespread among organisms                        | Numerous and variably distributed                                   |
| Production   | Associated with growth phase (trophophase)                  | Associated with non-growth phase (idiophase)                        |
| Quantity     | Generally produced in larger quantities                     | Usually accumulated in smaller quantities                           |
| Defence      | Generally not major defence compounds                       | Many participate in defence                                         |
| Examples     | Proteins, carbohydrates, lipids, amino acids, nucleic acids | Alkaloids, phenolics, sterols, steroids, essential oils and lignins |

### **Major structural metabolites and their functions**

The different structural metabolites do not perform identical functions. Instead, they form an integrated structural system. Cellulose provides tensile strength, hemicellulose connects cellulose fibres, pectin maintains adhesion between cells, lignin reinforces secondary walls and vascular tissues, while cutin and suberin create hydrophobic barriers. Callose provides rapid localized reinforcement at sites such as wounds, plasmodesmata and sieve plates.

### **Structural role in plant development and stress tolerance**

Structural metabolites support plant growth by maintaining cell shape and tissue organization and by changing their deposition as tissues differentiate. During vascular development, lignification provides the rigidity required for water-conducting tissues. Cellulose and hemicellulose provide the framework needed for controlled cell expansion, while pectin maintains adhesion between neighbouring cells. Protective outer polymers such as cutin and suberin reduce uncontrolled water movement and form barriers at interfaces between the plant and its environment. These

structural components also contribute to stress tolerance. Reinforced walls can reduce mechanical injury and pathogen penetration, hydrophobic barriers can limit water loss, and callose can be rapidly deposited at damaged sites. Structural and protective functions therefore overlap, with physical reinforcement providing the first line of resistance while chemical defence compounds provide additional protection.

### **Protective metabolites**

Protective metabolites are plant-derived compounds that protect plants from biotic and abiotic stresses by acting as physical, chemical or biochemical defence molecules. Most belong to secondary or specialized metabolism. They help plants respond to pathogens, herbivory, drought, salinity, heat, cold, UV radiation and oxidative damage. Some primary metabolites, including osmoprotective compounds, can also contribute to protection, but the presentation emphasizes secondary metabolites as the major group.

**Characteristics of protective metabolites:**  
**Alkaloids, phenolic compounds, flavonoids, terpenoids, phytoalexins, tannins, cyanogenic glycosides**



Protective metabolites are mainly defence-oriented, often low-molecular-weight compounds with strong biological activity. They may be constitutively present or induced following stress. Their distribution can be species-specific and they may accumulate in particular tissues such as leaves, bark, seeds, roots, fruits, trichomes and vacuoles. A single metabolite can perform more than one function, including antimicrobial, antioxidant, allelopathic, insecticidal and signalling activities. Alkaloids are nitrogen-containing secondary metabolites with strong biological activity. They can be toxic to insects and herbivores, inhibit microbial growth, affect insect nervous systems and reduce feeding. Important examples given in the presentation include nicotine in tobacco, caffeine in coffee and tea, morphine in the opium poppy and quinine in Cinchona. Phenolic compounds form a large group of aromatic compounds containing hydroxyl groups. They contribute to antioxidant activity, strengthen cell walls, inhibit pathogen growth, scavenge reactive oxygen species and protect plants against UV radiation. Examples include salicylic acid, tannins, gallic acid and ferulic acid. Flavonoids are polyphenolic pigments synthesized through the phenylpropanoid pathway. Their functions include antioxidant activity, UV protection and antimicrobial activity. They can also attract beneficial pollinators and function as signalling molecules in legume–Rhizobium interactions. Quercetin, kaempferol, anthocyanins and catechins are examples. Terpenoids constitute the largest class of plant secondary metabolites and are derived from isoprene units. They can repel insects, attract predators of herbivores and provide antifungal and antibacterial activity. They also contribute to protection against heat and oxidative stress. Examples include menthol from mint, limonene from citrus peel, artemisinin from sweet wormwood and pyrethrins from pyrethrum daisy.

Phytoalexins are antimicrobial compounds synthesized following pathogen attack. They help kill or inhibit fungi and bacteria, restrict pathogen spread and strengthen localized defence. Examples include resveratrol in grape, camalexin in Arabidopsis, pisatin in pea and phaseollin in bean. Tannins are polyphenolic compounds capable of binding proteins. By interacting with proteins and digestive enzymes, they reduce the digestibility of plant tissues and discourage herbivore feeding. They also show antimicrobial activity. The two major groups identified in the presentation are hydrolysable tannins and condensed tannins. Cyanogenic glycosides are compounds that can release hydrogen cyanide (HCN) when plant tissues are damaged. The released HCN makes damaged tissues toxic to herbivores and can disturb insect feeding and reduce pathogen survival. Examples include linamarin in cassava, dhurrin in sorghum and amygdalin in bitter almond.

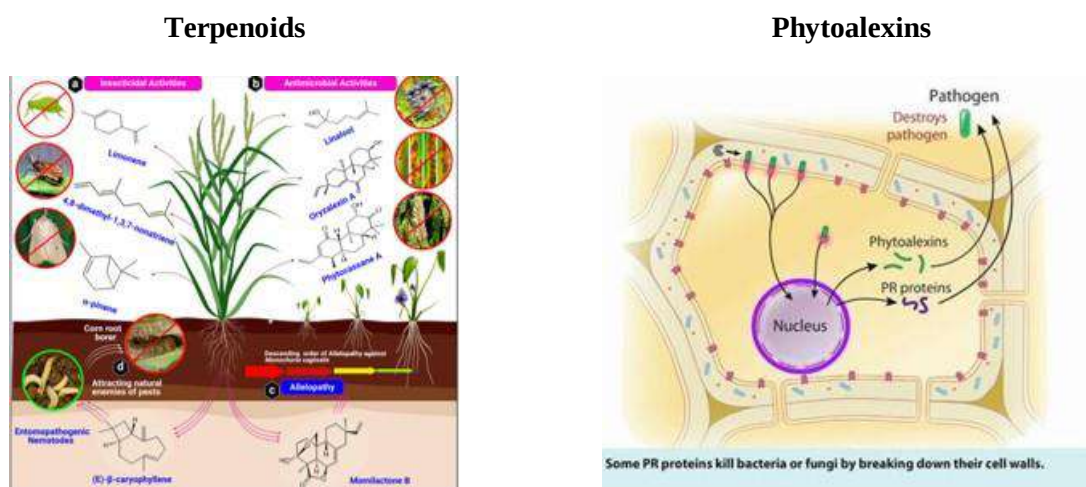
### **Secondary metabolites in plant defence**

Plants are sessile organisms and cannot escape pathogens, herbivores or environmental stresses. Consequently, they have evolved sophisticated defence systems based on secondary metabolites. When plants perceive stress signals, defence signalling pathways activate the biosynthesis and accumulation of specialized metabolites. These compounds may inhibit pathogen growth, deter herbivores, strengthen structural barriers and regulate defence-related gene expression.

### **Direct chemical defence**

In direct chemical defence, secondary metabolites act directly against pathogens or herbivores. They may be toxic, inhibit fungal and bacterial growth, reduce insect feeding or interfere with digestive enzymes. Nicotine, capsaicin and resveratrol are examples.

Fig.1: Protective metabolites



## Indirect ecological defence

Secondary metabolites can also protect plants indirectly by changing ecological interactions. After herbivore attack, plants may release volatile organic compounds that attract parasitoids or predators of the herbivores. These volatile signals can also function in communication and may warn neighbouring plants. Methyl jasmonate, monoterpenes and sesquiterpenes are examples associated with indirect defence.

## Defence against pathogens

Pathogens can enter plant tissues through natural openings or wounds. Plants respond through recognition of pathogen-associated signals followed by activation of defence pathways. Secondary metabolites can disrupt cell membranes and cell walls, inhibit enzymes and protein synthesis, damage DNA and suppress virulence-related processes. Phytoalexins are especially important because they are rapidly synthesized after infection and help restrict pathogen growth.

Table 2: Defensive function of metabolites

| Compound     | Defence function                |
|--------------|---------------------------------|
| Phytoalexins | Induced antimicrobial compounds |
| Phenolics    | Cell-wall strengthening         |
| Flavonoids   | Antifungal activity             |
| Lignin       | Physical barrier                |
| Tannins      | Protein precipitation           |
| Coumarins    | Antibacterial activity          |

## Defence Signalling

Secondary metabolites participate in signalling pathways that coordinate plant defence. Jasmonic acid (JA), salicylic acid (SA),

WRKY transcription factors and the MAP kinase cascade are important components identified in the presentation. Therefore, secondary metabolites are not simply toxic; they also regulate the timing and intensity



## Structural Defence

Secondary and specialized metabolites can contribute to structural defence by reinforcing the plant cell wall and reducing pathogen penetration. Lignin, suberin and callose strengthen or seal tissues and are important after damage or infection. This mechanism complements direct chemical defence by providing a physical barrier.

## Defence Against Herbivores

Plants produce toxic and deterrent metabolites that reduce herbivore feeding and survival. The presentation identifies neurotoxicity, reduced digestion, feeding deterrence, inhibition of oviposition and reduced insect growth as major modes of action.

**Table 3: Mode of action of metabolites**

| Compound       | Plant         | Function              |
|----------------|---------------|-----------------------|
| Nicotine       | Tobacco       | Neurotoxin            |
| Caffeine       | Coffee        | Feeding deterrent     |
| Capsaicin      | Chilli        | Mammalian deterrent   |
| Pyrethrin      | Chrysanthemum | Natural insecticide   |
| Glucosinolates | Brassica      | Toxic isothiocyanates |

## Secondary metabolites in antioxidant defence

Oxidative stress occurs when the production of reactive oxygen species (ROS) exceeds the antioxidant capacity of the plant. Secondary metabolites provide an important non-enzymatic antioxidant defence system. They can neutralize reactive molecules before irreversible cellular damage occurs and thereby contribute to plant survival under stress.

## Mechanisms of antioxidant action

Antioxidant secondary metabolites can directly scavenge free radicals and donate electrons or hydrogen atoms. They can also chelate transition metals such as  $\text{Fe}^{2+}$  and  $\text{Cu}^{2+}$ , prevent lipid peroxidation and stabilize cellular membranes. Phenolics and flavonoids are highlighted as particularly effective plant-derived antioxidants because they can donate electrons and stabilize free radicals.

## Hormonal regulation of secondary metabolites

Secondary metabolite production is regulated by plant hormones that coordinate defence responses. Jasmonic acid is associated with insect attack, wounding and necrotrophic pathogens and stimulates the production of alkaloids, terpenoids and volatile organic compounds. Salicylic acid is associated with biotrophic pathogens and stimulates phenolics, pathogenesis-related proteins, flavonoids and phytoalexins. Transcription factors such as WRKY, MYB, MYC2 and ERF participate in regulating the expression of defence-related genes. Jasmonic acid is synthesized from the membrane fatty acid  $\alpha$ -linolenic acid. Following tissue damage or herbivore attack, lipoxygenase initiates the pathway and produces oxylipin intermediates that ultimately lead to OPDA and jasmonic acid. Jasmonic acid can be conjugated with isoleucine to form JA-Ile, an important bioactive signal.

## Biosynthetic pathways of secondary metabolites

Secondary metabolites are synthesized from primary metabolic precursors through specialized biosynthetic pathways. The



presentation identifies the shikimate pathway, phenylpropanoid pathway, mevalonate pathway, MEP pathway and alkaloid pathways as major routes contributing to the diversity of secondary metabolites.

### **Shikimate and phenylpropanoid pathways**

The shikimate pathways connects primary carbohydrate metabolism with the production of aromatic amino acids, particularly phenylalanine, tyrosine and tryptophan, hence important for plant metabolism. These amino acids subsequently serve as precursors for many secondary metabolites. The phenylpropanoid pathway uses phenylalanine as a major precursor and contributes to the biosynthesis of phenolics, flavonoids, lignin, coumarins and phytoalexins.

### **References**

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### **Conclusion**

Secondary metabolites represent a major component of plant specialized metabolism and are essential for plant interaction with the environment. Structural metabolites maintain the physical organization and strength of plant tissues, whereas protective metabolites provide chemical and biochemical defence. Their functions include pathogen inhibition, herbivore deterrence, antioxidant protection, structural reinforcement and signalling. Hormones such as jasmonic acid and salicylic acid coordinate their production, while specialized biosynthetic pathways convert primary metabolic precursors into diverse protective compounds. Together, structural and protective metabolites provide complementary mechanisms that enhance plant survival, defence and adaptation.

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