Chapter 4
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Bioactive Secondary Metabolites: A Natural Blueprint Towards Therapeutic Approach

Amanpreet Kaur [a*], Shubhangee Agarwal [a], Priyanka Rani [a], Pawan Kumar Shukla [a] and Neha Bhatt [b]

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ABSTRACT

Secondary metabolites are a varied array of organic molecules synthesised by plants, microbes, and some animals that, while not directly associated with growth or reproduction, are essential for ecological interactions and defensive strategies. Compounds such as alkaloids, flavonoids, steroids, saponins, and terpenoids have attracted considerable interest owing to their broad uses in the medicinal, agricultural, cosmetic, and food sectors. Alkaloids are recognised for their strong pharmacological effects, flavonoids for their antioxidant capabilities, steroids for hormonal modulation, saponins for their antibacterial and immunomodulatory functions, and terpenoids for their extensive therapeutic potentials. Advancements in biotechnology, green chemistry, and artificial intelligence are transforming the discovery, extraction, and use of these natural compounds. Moreover, increasing environmental consciousness is propelling the transition to sustainable sourcing and manufacturing techniques. This chapter offers a comprehensive examination of the significance of secondary metabolites, addresses their many uses, and investigates future opportunities for their use in developing more sustainable and health-oriented solutions across several industries.

Keywords: Secondary metabolites; flavonoids, alkaloids; terpenoids; saponins.

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[a] *Department of Chemistry, School of Sciences, IFTM University, Moradabad-244102, Uttar Pradesh, India.*
[b] *Department of Chemistry, Pt. L.M.S., Rishikesh Campus, SDS University, Tehri Garhwal- 249145, Uttarakhand, India.*
**Corresponding author: E-mail: amanpreet2225@gmail.com;*

1. INTRODUCTION

Secondary metabolites are a compelling and vital category of naturally occurring molecules that, although not directly engaged in fundamental growth, development, or reproductive activities, provide considerable adaptive benefits to organisms. In general, secondary metabolites are the product of primary metabolites and are produced from biosynthesis modifications, including methylation, glycosylation and hydroxylation. These small organic molecules (having molecular masses of less than 3000 Da) are certainly more complex in structural composition and side chains compared to primary metabolites (Gallardo and Seca, 2022; Elshafie et al., 2023; Kumar et al., 2023). Secondary metabolites, mostly located in plants, fungi, bacteria, and some marine creatures, have developed over millions of years as a component of intricate ecological interactions. They serve as chemical defences against herbivores, diseases, and competitors, while also acting as attractants for pollinators and seed dispersers, so playing a crucial role in the survival and evolutionary success of species (Jeyasri et al., 2023; Soltanbeigi and Soltani, 2024). In contrast to main metabolites like carbohydrates, proteins, and lipids, secondary metabolites have significant structural variety and complexity. This variety results in a broad spectrum of biological functions, making them very beneficial for human uses (Tariq et al., 2023). Compounds include alkaloids, flavonoids, steroids, saponins, and terpenoids have been central to traditional medicine for millennia and continue to influence contemporary pharmacological research and commercial advancements. Their significant bioactivities, including antibacterial, antioxidant, anticancer, anti-inflammatory, and immunomodulatory properties, have resulted in the creation of several medicinal agents and functional items (Chen et al., 2022). In addition to their pharmacological importance, secondary metabolites are gaining recognition in agriculture for their contributions to the creation of biopesticides, biofertilizers, and plant growth regulators, providing sustainable alternatives to synthetic agrochemicals. In the cosmetic sector, natural substances like flavonoids and terpenoids are esteemed for their antioxidant and anti-ageing attributes, but in the food sector, saponins and other secondary metabolites improve nutritional content, shelf-life, and safety of food items (Twaij and Hasan, 2022). Recent breakthroughs in biotechnology, metabolomics, and synthetic biology have established new avenues for the investigation and use of secondary metabolites. Advancements in extraction technology, microbial fermentation, and metabolic engineering are facilitating the more efficient and sustainable manufacture of these important molecules. Simultaneously, the rising global consciousness of environmental sustainability and customer preference for natural goods are propelling the investigation of more sustainable and ethical approaches to secondary metabolite usage (Noushahi et al., 2022). This chapter examines the significance of secondary metabolites, emphasising the roles of major categories including alkaloids, flavonoids, steroids, saponins, and terpenoids. It examines their extensive uses across diverse industries, analyses technological breakthroughs affecting their manufacturing and utilisation, and contemplates future research and industrial application trajectories (Wu et al., 2021).

2. TYPES OF SECONDARY METABOLITES

2.1 Flavonoids

Flavonoids, an essential category of secondary metabolites, are phenolic chemicals that account for the vibrant colours of several fruits and flowers. Nonetheless, their functions are beyond mere looks. Flavonoids function as potent antioxidants, counteracting detrimental free radicals and so safeguarding cells from oxidative stress (Zhang et al., 2020). This feature has been associated with the protection of chronic illnesses, including cancer, cardiovascular problems, and neurological diseases (Hemmerlin, 2023). Quercetin, a notable flavonoid, has shown significant anti-inflammatory and antiviral properties, resulting in its incorporation into dietary supplements and functional foods. Besides their health advantages, flavonoids serve as natural colourants and preservatives in the food sector, providing an alternative to synthetic chemicals sometimes linked to health issues. Their UV-protective properties render them essential components in sunscreens and anti-ageing cosmetics (Yap et al., 2020).

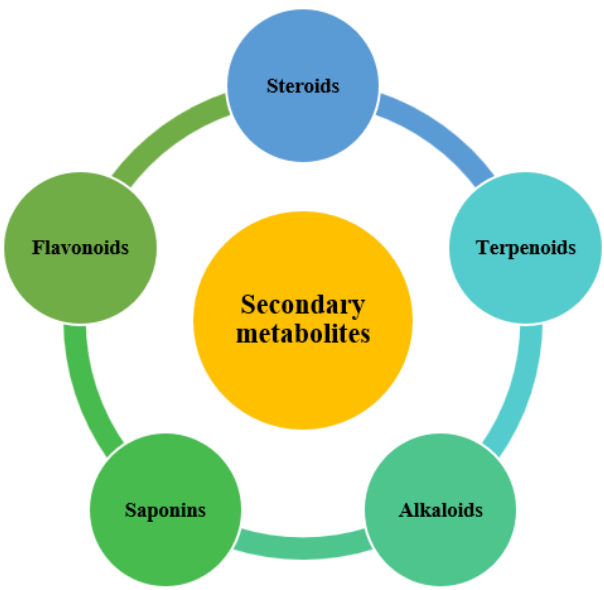

Fig. 1. Types of secondary metabolites

2.2 Steroids

Steroids, defined by their cyclopentanoperhydrophenanthrene ring structure, are essential in biological systems as hormones, vitamins, and components of membranes (Huang et al., 2022). Their medicinal importance is substantial.

Corticosteroids such as dexamethasone are extensively used for the management of inflammatory and autoimmune disorders, while anabolic steroids, despite their contentious application, are therapeutically employed to address muscle wasting illnesses. The COVID-19 pandemic highlighted the significance of steroids such as dexamethasone in decreasing mortality among critically sick patients (Del Mondo et al., 2022). Steroidal glycoalkaloids derived from plants such as Solanum species have inherent pesticidal properties in agriculture. The cosmetic industry utilises the anti-inflammatory effects of certain steroids to develop treatments for skin disorders like eczema, psoriasis, and dermatitis (Ayoola-Oresanya et al., 2021).

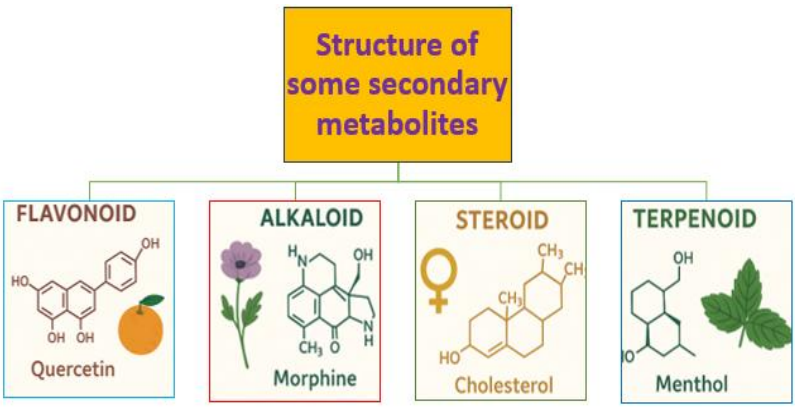

Fig. 2. Structure of some Secondary metabolites

2.3 Saponins

Saponins, characterised by their soap-like foaming characteristics, are glycosides that have garnered interest for their diverse biological functions. They demonstrate considerable antibacterial, anticancer, and immunostimulatory properties. Saponins have been used as vaccine adjuvants, augmenting immune responses to infections (Marchin et al., 2022). Quillaja saponins have been used in the development of contemporary vaccines. Saponins function as natural emulsifiers and preservatives in the food industry, prolonging shelf life while preserving product integrity. Their insecticidal and antifungal activities are being investigated as eco-friendly substitutes for conventional pesticides in agriculture. Furthermore, the cosmetic sector integrates saponins into shampoos, cleansers, and other personal care products due to their natural surfactant qualities, which enhance skin and hair health (Han et al., 2022).

2.4 Terpenoids

Terpenoids, the most extensive class of secondary metabolites, are structurally varied molecules originating from isoprene units. Their importance encompasses

almost all major industries. In medicine, terpenoids have led to the development of powerful pharmaceuticals, including artemisinin, an antimalarial compound sourced from Artemisia annua, and paclitaxel (Taxol), a chemotherapy medication extracted from the Pacific yew tree (Koza et al., 2022). Terpenoids constitute the fundamental structure of several essential oils, used in aromatherapy, perfumery, and natural treatments for diverse disorders. Terpenoids serve as natural herbicides, insecticides, and growth regulators in agriculture, promoting sustainable farming techniques. Their aromatic characteristics render them vital components in flavouring and scents, while their antioxidant qualities have been used in the development of natural preservatives (Zhao et al., 2021).

2.5 Alkaloids

Alkaloids constitute a broad and pharmacologically important category of secondary metabolites mostly derived from plants, while others are synthesised by fungi, bacteria, and mammals. Alkaloids, defined by nitrogen atoms often found in heterocyclic rings, have a diverse array of biological functions, making them essential in medicine and business (Zahid et al., 2023). Historically, alkaloids like morphine, quinine, and atropine were among the first natural chemicals isolated for medicinal use, offering significant analgesic, antimalarial, and anticholinergic properties, respectively. Currently, alkaloids remain pivotal as lead chemicals in therapeutic discovery and development, with applications in analgesia, cardiovascular therapy, antibacterial treatment, and anticancer treatments. In addition to their pharmacological use, alkaloids play a significant role in agriculture as natural pesticides and growth regulators (Aliniaeifard et al., 2023). Their ecological functions, mainly in protection against herbivores and diseases, demonstrate their significant bioactivities, which humans have used for medicinal and defensive applications. Progress in biotechnology and synthetic biology is augmenting the possibilities for sustainable alkaloid synthesis and structural alteration, providing avenues to boost effectiveness, diminish toxicity, and identify new derivatives with superior pharmacological characteristics. As worldwide health difficulties progress, the investigation and utilisation of alkaloids are anticipated to be pivotal in the advancement of next-generation medicines and sustainable agricultural methodologies (Zhao et al., 2024).

2.6 Application

Secondary metabolites affect several sectors. Secondary metabolites underlie antibiotics like penicillin and erythromycin, anticancer drugs, cardiovascular drugs, and immunosuppressants. Due to antibiotic resistance and developing diseases as COVID-19, secondary metabolites are being studied more to find novel drugs. Recent studies suggest that plant-derived secondary metabolites may inhibit SARS-CoV-2 replication, opening up new drug development prospects (Wadhwa et al., 2024).

The move toward sustainable agriculture has emphasised secondary metabolites' biocontrol value. Farmers are utilising bio-pesticides made from

plant secondary metabolites instead of synthetic agrochemicals, which may harm the environment. Terpenoids make neem oil a powerful insect repellent and growth inhibitor. Saponins and flavonoids may increase plant resilience to pests and diseases, reducing the requirement for chemical treatments (Al Aboud, 2024; Wu et al., 2025).

Food and beverage companies have also benefited from secondary metabolites' functions. Flavonoids and anthocyanins as natural food colourants meet customer desire for artificial-free products (Nordine, 2025). Flavonoids and terpenoids reduce lipid peroxidation and microbiological growth, extending shelf life and nutritional integrity. Proanthocyanidins, flavonoids, are being included in cardiovascular health nutraceuticals (Wu et al., 2025).

The cosmetic industry's interest in secondary metabolites has grown, especially with natural and organic skincare trends. Flavonoids and terpenoids protect the skin against UV radiation and pollution-induced oxidative damage (Nordine, 2025). Secondary metabolites provide anti-ageing, brightening, and anti-inflammatory benefits. Saponins, which clean gently, are favoured in natural shampoos and face cleansers over synthetic surfactants (Swain et al., 2022).

3. FUTURE OUTLOOK

A promising era of secondary metabolite research and usage will include technological integration, sustainability, and global health challenges. Secondary metabolites will remain important in the pharmaceutical, agricultural, cosmetic, and food industries as customers seek ecologically friendly, safe, and effective natural products. A major progress avenue is synthetic biology. Genome editing technologies, notably CRISPR-Cas9, may let plants and bacteria accurately modify biosynthetic pathways to produce more valuable secondary chemicals. Researchers are using yeast and bacterial strains to industrially synthesise complex plant alkaloids and terpenoids, potentially overcoming natural sources' yield and habitat destruction issues (Swain et al., 2022). AI and ML are also changing natural product research. Predictive modelling, cheminformatics, and AI-driven screening algorithms optimise secondary metabolite discovery for particular biological roles. These tools allow researchers to quickly uncover lead compounds from large natural libraries, saving time and money (Sahoo et al., 2022). The cooperation between biotechnology and digital technologies is likely to revive natural drug development. Future studies will focus on sustainability. Traditional extraction methods consume plenty of organic solvents and resources. Supercritical fluid extraction, microwave-assisted extraction, and biocatalysis are greener alternatives. These methods will be used more to reduce environmental harm and meet global regulatory standards. Secondary metabolites can help the pharmaceutical sector fight antibiotic resistance, a rising public health issue. Natural compounds have unique mechanisms of action, making them useful for developing next-generation antibiotics. Secondary metabolites' antiviral activity is encouraging, especially given the threat of novel viral infections. Plant flavonoids, terpenoids, and alkaloids are being studied for their ability to block viral entry and reproduction, suggesting that nature-based

medicines may treat future pandemics (Sahoo et al., 2022). Secondary metabolites are transforming agriculture toward sustainability. As synthetic pesticides and fertilisers become scarcer, secondary metabolite-derived biopesticides and biofertilisers provide a sustainable alternative. Maintaining food security in changing climates requires studying saponins, terpenoids, and flavonoids to boost plant defence and insect resistance. Cosmetic and food companies will continue to use secondary metabolites' multifunctional properties to meet consumer demand for natural, functional, and ethical products. Due to their antioxidant and anti-inflammatory properties, flavonoids and terpenoids are expected to dominate future cosmetics and nutraceuticals that improve lifespan and health. Secondary metabolite research will also help safeguard world biodiversity. Rare or endangered species provide several valuable secondary metabolites. Documenting, protecting, and exploiting biodiversity hotspots responsibly is crucial. Integrating old knowledge with modern science, ethnobotanical research will continue to provide useful insights from indigenous medical traditions, promoting ethical and innovative bioprospecting.

4. CONCLUSION

Secondary metabolites, a rich source of bioactive molecules for medicine, agriculture, food, and cosmetics, are one of nature's greatest gifts. Alkaloids, flavonoids, steroids, saponins, and terpenoids demonstrate the chemical complexity and evolutionary brilliance of living creatures, serving as defensive mechanisms in nature and life-saving medications and health-promoting agents in humans. Their antibacterial, antioxidant, anticancer, anti-inflammatory, and immunomodulatory properties make them essential to medicinal and functional product development. Their function in sustainable agriculture via natural insecticides and plant-growth stimulants shows their importance to environmental issues.

Biotechnology, metabolomics, synthetic biology, and artificial intelligence are accelerating secondary metabolite discovery, production, and optimisation, offering new opportunities for innovation while emphasising sustainable and ethical methods. Secondary metabolites are predicted to become more important in health care, environmental protection, and business as the worldwide demand for natural, safe, and effective solutions rises. Their future depends on biodiversity protection, appropriate bioprospecting, and multidisciplinary research that respects scientific advances and traditional knowledge systems. Secondary metabolites are biological mysteries and potent instruments that connect nature and human development. Their study and implementation show great potential for a healthier, more sustainable future, proving their relevance in scientific research, industrial innovation, and environmentalism.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

The authors affirm that no artificial intelligence (AI) tools or automated content generation systems were used in the writing, editing, analysis, or preparation of

this manuscript. All work presented is original and solely the result of the authors' efforts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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