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AMIDE-CONTAINING SECONDARY METABOLITES FROM MEDICINAL PLANTS: DISTRIBUTION, BIOLOGICAL ROLES, AND DRUG DISCOVERY POTENTIAL

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ABSTRACT

Medicinal plants represent one of the most important sources of structurally diverse bioactive molecules used in modern drug discovery. Among plant secondary metabolites, amide-containing natural products constitute a chemically versatile and biologically significant class that has received comparatively limited systematic attention. These compounds include phenolic acid amides, alkaloid-derived amides, fatty-acid amides, hormone-conjugated amides, and structurally diverse nitrogen-linked derivatives distributed across numerous plant families and associated microorganisms. Increasing phytochemical and pharmacological investigations demonstrate that plant amide metabolites participate in defence signalling, environmental adaptation, and metabolic regulation while also exhibiting diverse therapeutic activities including anti-inflammatory, antimicrobial, cytotoxic, antiparasitic, and metabolic regulatory effects. Recent developments in metabolomics, artificial-intelligence-assisted screening, and multi-omics natural-product discovery platforms have further accelerated the identification of novel amide scaffolds. This review provides a comprehensive overview of the occurrence, biosynthetic relevance, biological functions, and pharmaceutical potential of amide-containing secondary metabolites from medicinal plants.

KEYWORDS: Amide-containing natural products, Medicinal plants, Plant secondary metabolites, Natural-product drug discovery, Bioactive phytochemicals.

1. INTRODUCTION

Medicinal plants have long served as one of the most prductive sources of therapeutic agents, contributing significantly to both traditional medicine and modern pharmaceutical development.[1,4] A large proportion of clinically used drugs either originate directly from natural products or are structurally inspired by plant-derived molecules.[3,5] The chemical richness of plant metabolites reflects millions of years of evolutionary selection, resulting in compounds optimized for biological interaction, molecular recognition, and ecological function.[2,4]

Plant secondary metabolites are structurally diverse organic molecules not directly required for primary metabolism but essential for plant survival, ecological communication, and environmental adaptation.[6,9] These compounds include alkaloids, terpenoids, phenolics, flavonoids, and nitrogen-containing conjugates that collectively regulate plant defence, pathogen resistance, stress signalling, and reproductive biology.[7,10] Modern molecular investigations show that their biosynthesis is tightly controlled by transcriptional regulators, signalling pathways, and environmental stimuli such as light, temperature, and pathogen exposure.[9,11,12]

Among nitrogen-containing plant metabolites, amide-containing compounds represent a structurally important yet comparatively underexplored group. The amide functional group provides conformational stability, hydrogen-bonding capacity, and metabolic persistence, allowing these molecules to interact effectively with biological macromolecules. Natural amide metabolites arise through enzymatic conjugation between carboxylic acids and amines, integrating carbon and nitrogen metabolic pathways.[13]

Recent phytochemical surveys have revealed the widespread distribution of phenolic acid amides, alkaloid-derived amides, fatty-acid amides, and jasmonate conjugates across medicinal plant species.[13,14] In addition to their biological roles within plant systems, many natural amide metabolites exhibit pharmacological activities relevant to human health, including anti-inflammatory, antimicrobial, antidiabetic, cytotoxic, and antiparasitic effects.[15,18]

With the growing demand for novel drug leads and the emergence of advanced discovery platforms integrating ethnobotany, metabolomics, and artificial intelligence, plant-derived amide scaffolds have gained increasing importance in pharmaceutical research.[9,19,22]

Therefore, the present review aims to systematically examine the distribution, biological functions, and drug-discovery potential of amide-containing secondary metabolites from medicinal plants.

To provide a conceptual framework for understanding the origin, biological roles, and therapeutic significance of plant-derived amide metabolites, a schematic overview of their biosynthesis, physiological functions, pharmacological activities, and relevance in drug discovery is presented in **Figure 1**.

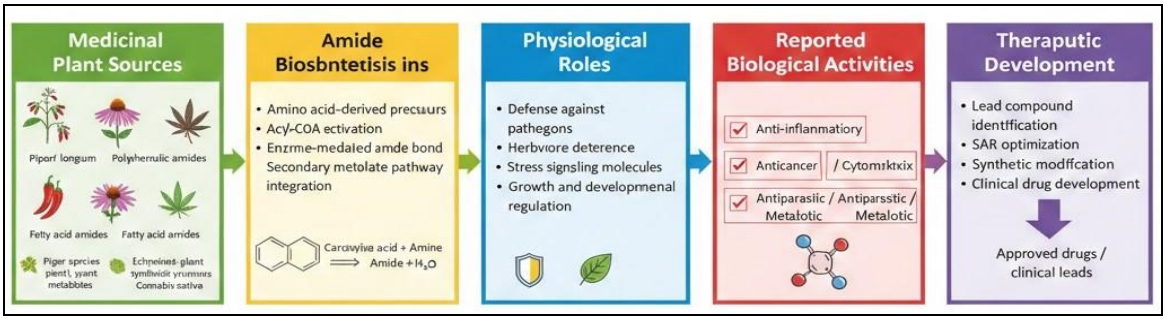

Figure 1: Plant-Derived Amide Metabolites: From Biosynthesis to Therapeutic Applications.

2. Distribution of Amide-Containing Secondary Metabolites

Amide-containing secondary metabolites are widely distributed across the plant kingdom and represent an important chemical class linking nitrogen metabolism with phenylpropanoid, fatty acid, and hormone biosynthetic pathways. These metabolites occur in diverse plant organs, including leaves, seeds, roots, fruits, and reproductive tissues, and often show species-specific accumulation patterns reflecting ecological adaptation and evolutionary selection pressures. Modern phytochemical investigations demonstrate that the occurrence of amide metabolites is not restricted to a single biosynthetic lineage but instead spans multiple structural subclasses such as phenolic acid amides, alkaloid-derived amides, hormone conjugates, and microbially derived amide analogues.[13,18]

The spatial distribution of these metabolites frequently correlates with plant defence requirements, developmental stages, and environmental stress exposure. In many medicinal plants, amide metabolites are concentrated in tissues that function as protective barriers against herbivores, pathogens, or oxidative stress, indicating their functional importance beyond simple metabolic intermediates.[8,9]

Plant-derived amide metabolites encompass multiple structurally distinct subclasses formed through diverse biosynthetic routes, and their principal chemical categories are summarized in **Figure 2**.

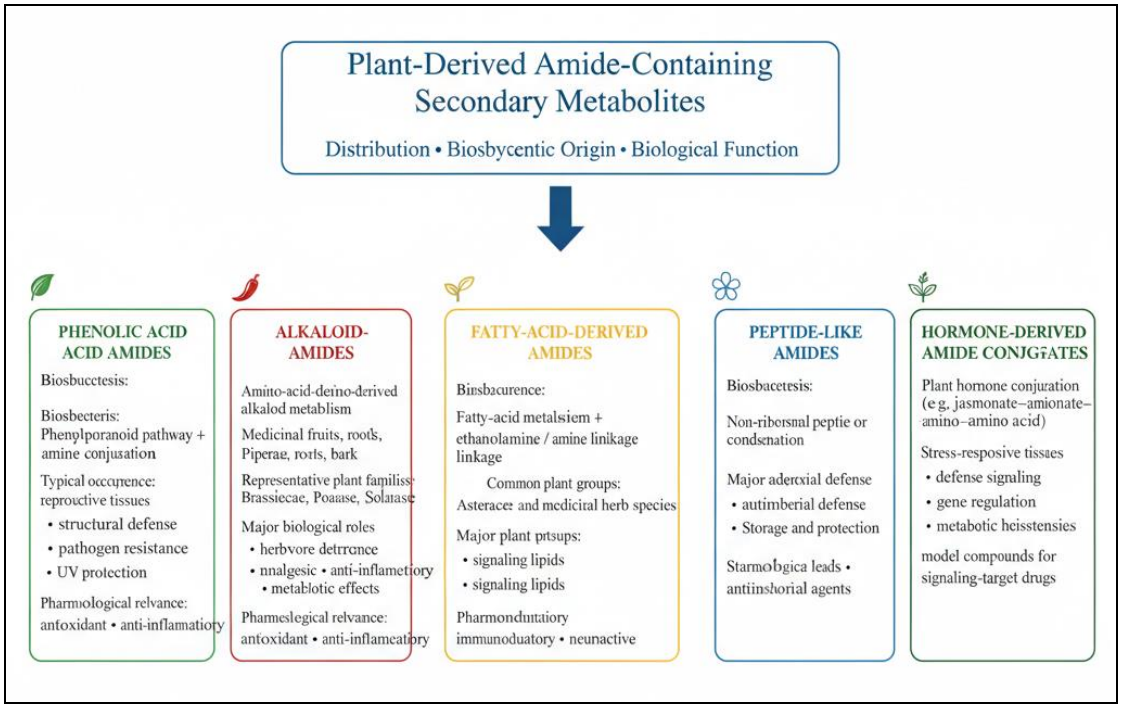

Figure 2: Structural and Functional Classes of Plant-Derived Amide Metabolites.

2.1 Phenolic Acid Amides

Phenolic acid amides represent one of the most extensively studied and widely distributed subclasses of plant amide metabolites. These compounds are generally formed through enzymatic conjugation of hydroxycinnamic acids—such as *p*-coumaric, ferulic, or caffeic acids—with various aromatic or aliphatic amines including tyramine, putrescine, agmatine, or spermidine. Comprehensive phytochemical surveys confirm their occurrence across numerous plant families, including Solanaceae, Brassicaceae, Poaceae, Asteraceae, and Leguminosae.[13]

Structurally, phenolic amides exhibit substantial diversity due to variations in both the phenolic acid component and the amine moiety, producing mono-, di-, and poly-substituted derivatives with differing polarity, reactivity, and biological function. Many of these compounds accumulate preferentially in reproductive tissues such as pollen, seeds, and fruit pericarps, where they contribute to structural reinforcement, UV protection, and microbial resistance. Their enrichment in protective outer tissues strongly suggests a defensive ecological function.

From a biosynthetic perspective, phenolic amides arise through the action of BAHD-family acyltransferases that catalyse coupling reactions between activated hydroxycinnamoyl-CoA esters and amine acceptors. This biochemical linkage integrates phenylpropanoid metabolism with nitrogen assimilation pathways, thereby connecting primary and secondary metabolic networks.[13]

Environmental stimuli strongly influence phenolic amide biosynthesis. Experimental studies demonstrate that pathogen invasion, mechanical injury, ultraviolet irradiation, and oxidative stress can significantly enhance the accumulation of hydroxycinnamic acid amides in plant tissues. Such inducible synthesis patterns further support their role as adaptive chemical defence molecules involved in plant protection and stress tolerance.[8,9]

2.2 Alkaloid-Derived Amide Metabolites

Alkaloid-derived amide metabolites constitute another structurally complex and pharmacologically significant group of plant natural products. These compounds often combine classical alkaloid frameworks with amide linkages, generating hybrid molecular architectures capable of interacting with multiple biological targets.

Medicinal plants belonging to the Piperaceae family have proven to be particularly rich sources of such amide-linked alkaloids. Advanced phytochemical investigations have identified structurally unusual dimeric amide alkaloids and related derivatives from species such as *Piper nigrum* and *Piper longum*, demonstrating the remarkable structural diversity achievable through amide coupling reactions in natural biosynthesis.[16,17]

Biological evaluation of these metabolites has revealed diverse pharmacological properties. Recent studies describe anti-inflammatory amide-alkaloid dimers isolated from medicinal plant roots that exhibit significant immunomodulatory effects, suggesting potential therapeutic applications in inflammatory disorders.[16] Likewise, dimeric amide alkaloid enantiomers obtained from medicinal plants have demonstrated both anti-inflammatory and antidiabetic activities, highlighting the ability of amide-linked alkaloid scaffolds to modulate multiple disease pathways simultaneously.[17]

Such findings emphasize that amide incorporation into alkaloid frameworks is not merely a structural modification but often enhances molecular stability, target affinity, and

pharmacological potency, thereby contributing to the medicinal relevance of these compounds.

2.3 Jasmonate-Derived Amide Conjugates

In addition to structurally defensive metabolites, plants also produce hormone-derived amide conjugates that function as regulatory signalling molecules. Among these, jasmonate-related amide conjugates represent a particularly important class controlling plant growth, development, and stress responses.

Experimental studies demonstrate that conjugation of jasmonate precursors through amide bond formation directly regulates hormone homeostasis by controlling biosynthetic flux, intracellular transport, and degradation pathways. Such conjugates modulate signalling cascades responsible for defence gene activation, wound responses, and pathogen resistance mechanisms.[14]

Importantly, these observations establish amide formation as an essential biochemical regulatory mechanism rather than a simple detoxification or storage process. By altering hormone stability and receptor interactions, amide conjugation provides plants with a rapid and reversible method of tuning physiological responses to environmental challenges.[14]

2.4 Microbial and Endophytic Sources Associated with Medicinal Plants

The total diversity of amide metabolites associated with medicinal plants extends beyond compounds synthesized directly by plant tissues. Plant-associated endophytic microorganisms—including fungi and bacteria—frequently produce structurally diverse amide-containing secondary metabolites that contribute to the overall chemical ecology of the plant host.

Investigations of endophytic fungal strains isolated from medicinal plants have yielded novel cytotoxic amide derivatives, including compounds derived from phenolic acid and terpenoid precursors. These findings demonstrate that plant-microbe symbiosis represents an additional and often overlooked source of bioactive amide metabolites.[18]

Such microbial metabolites may function as chemical defence agents, ecological signalling molecules, or synergistic pharmacological contributors within medicinal plant extracts. Consequently, the true distribution of amide-containing secondary metabolites should be

viewed as a combined product of plant biosynthesis and associated microbial metabolism, significantly expanding the chemical space available for natural-product drug discovery.

Numerous structurally diverse amide metabolites have been experimentally identified from medicinal plants and associated microorganisms. Representative examples illustrating their taxonomic distribution, structural subclasses, and reported biological functions are summarized in Table 1.

Table 1: Natural amide metabolites reported from medicinal plants and associated biological activities.

Class of Amide	Representative Compound / Type	Plant Source	Plant Family	Major Reported Biological Role / Activity	Ref.
Phenolic acid amide	p-Coumaroyl tyramine	*Solanum lycopersicum*	Solanaceae	Stress-induced defence metabolite; antimicrobial role	[13]
Phenolic acid amide	Feruloyl putrescine	*Arabidopsis thaliana*	Brassicaceae	Cell-wall reinforcement; pathogen response	[13]
Phenolic acid amide	Caffeoyl spermidine derivatives	*Helianthus annuus*	Asteraceae	UV protection and reproductive tissue defence	[13]
Phenolic acid amide	Hydroxycinnamoyl agmatine derivatives	Various cereals	Poaceae	Resistance against fungal infection	[8,9,13]
Alkaloid-derived amide	Amide–alkaloid dimers	*Piper nigrum*	Piperaceae	Strong anti-inflammatory activity	[16]
Alkaloid-derived amide	Dimeric amide alkaloid enantiomers	*Piper longum*	Piperaceae	Anti-inflammatory and antidiabetic activity	[17]
Alkaloidal amide	Piperamide derivatives (general class)	Multiple *Piper* species	Piperaceae	Broad antimicrobial and medicinal importance	[16,17]
Hormone-derived amide	OPDA-amide conjugates	Various higher plants	Multiple families	Regulation of jasmonate homeostasis and stress signalling	[14]
Hormone-derived amide	Jasmonate amino-acid conjugates	Higher plants (general)	Multiple families	Defence signalling and wound response	[14]
Endophyte-associated amide	p-Hydroxybenzoic acid-derived amides	Endophytic fungi from medicinal plants	—	Cytotoxic and bioactive metabolites	[18]
Endophyte-derived amide	Sesquiterpene-linked amides	Endophytic fungal strains	—	Potential anticancer activity	[18]

3. Biological Roles of Plant Amide Metabolites

Plant amide-containing secondary metabolites perform diverse biological functions that extend beyond simple structural or metabolic intermediates. These compounds participate in plant defence, environmental adaptation, intracellular signalling, and developmental regulation. Because amide formation frequently modifies molecular polarity, stability, and protein-binding properties, the incorporation of amide linkages often enhances the functional versatility of plant secondary metabolites in ecological and physiological processes,[7,9]

The formation and biological activity of plant-derived amide metabolites arise from interconnected biosynthetic pathways that integrate environmental signals, nitrogen metabolism, and phenylpropanoid or lipid intermediates. These relationships are summarized schematically in **Figure 3.**

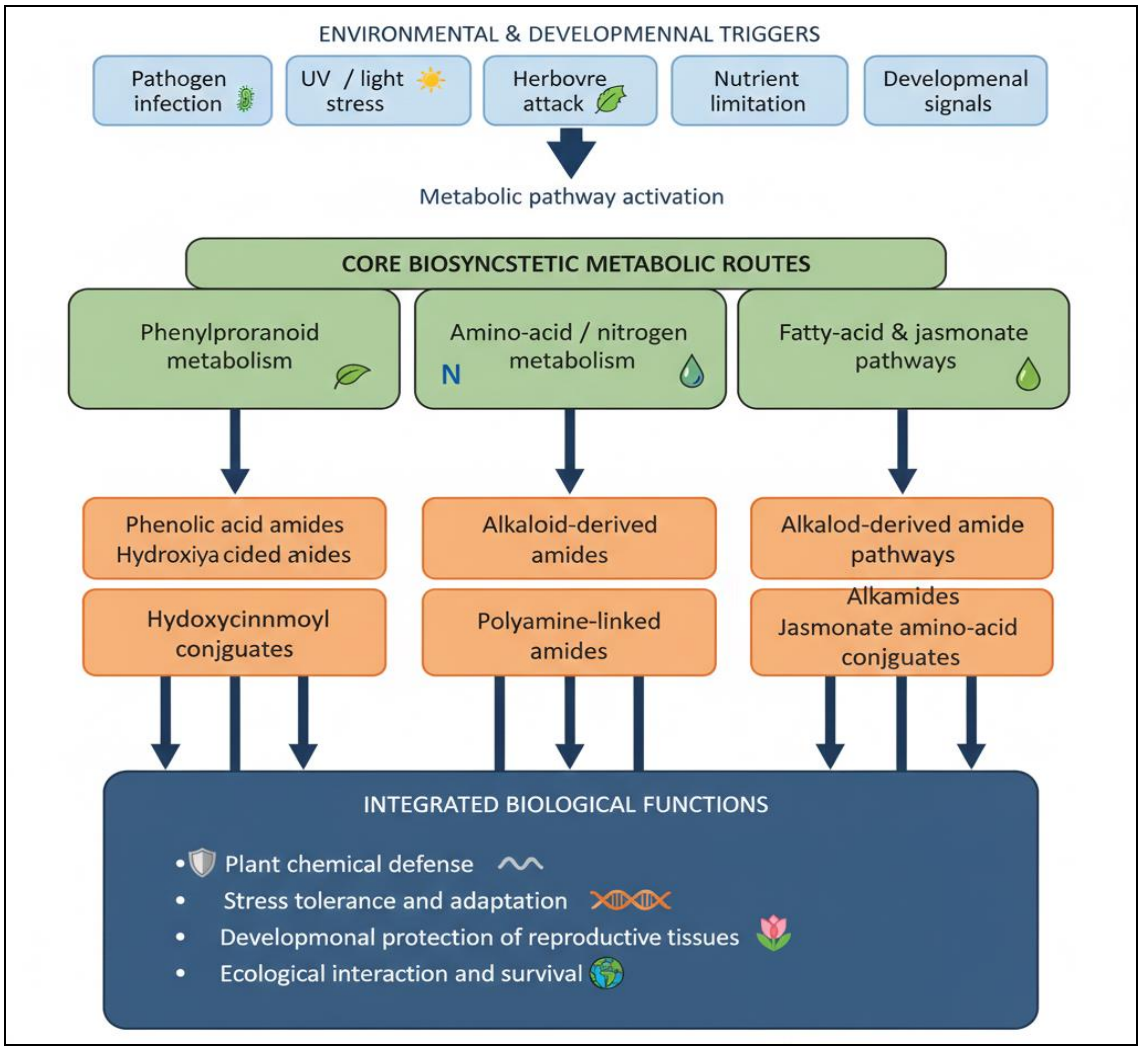

Figure 3: Integrated Biosynthetic and Functional Network of Plant-Derived Amide Metabolites.

3.1 Chemical Defence Mechanisms

Secondary metabolites, including numerous amide derivatives, function as chemical defence agents protecting plants against microbial pathogens, herbivorous insects, and environmental stressors such as oxidative damage or UV radiation.[7,9] Many phenolic amides and alkaloid-linked amide metabolites possess antimicrobial, antifungal, or deterrent properties that reduce pathogen colonization and herbivore feeding.

Importantly, the biosynthesis of these metabolites is typically inducible rather than constitutive. Their concentrations often increase rapidly following pathogen infection, wounding, or mechanical injury, demonstrating their role as part of an activated plant immune response.[8] Such inducible accumulation is commonly associated with activation of phenylpropanoid metabolism, enhanced nitrogen mobilization, and transcriptional upregulation of biosynthetic enzymes involved in amide formation.

In addition to direct toxicity toward pathogens, certain amide metabolites also contribute to strengthening of plant structural barriers by promoting cell-wall cross-linking or oxidative polymerization reactions. This dual function—chemical toxicity combined with structural reinforcement—makes amide-containing metabolites particularly effective components of plant defence strategies.

3.2 Stress Signalling and Hormonal Regulation

Beyond their defensive roles, amide conjugates participate in essential regulatory signalling pathways that control plant adaptation to environmental and biological stresses. Hormone-derived amide intermediates, especially those associated with jasmonate metabolism, play direct roles in regulating defence gene activation, stress tolerance mechanisms, and metabolic homeostasis.[14]

Amide formation within hormone pathways can influence hormone transport, storage stability, receptor recognition, and degradation kinetics. Consequently, conjugation reactions involving jasmonate precursors or related signalling molecules provide plants with a dynamic biochemical mechanism for fine-tuning stress responses in a rapid and reversible manner.

Recent transcriptional and molecular studies further demonstrate that secondary metabolite production—including nitrogen-containing metabolites—is tightly regulated by transcription factors such as MYC2 and associated regulatory proteins that integrate environmental stimuli

with biosynthetic gene expression.[11,12] These transcriptional networks coordinate signalling pathways controlling both primary metabolism and defensive secondary metabolite synthesis, thereby ensuring that amide metabolite production is aligned with physiological needs and environmental pressures.

3.3 Environmental and Developmental Regulation

External environmental factors strongly influence the production and accumulation of plant secondary metabolites, including amide-containing compounds. Light exposure, temperature variation, water availability, nutrient status, and abiotic stress conditions have all been shown to modulate metabolite biosynthesis.

Light-regulated metabolic pathways, in particular, play a major role in controlling the accumulation of protective secondary metabolites. Experimental evidence indicates that photoreceptor-mediated signalling cascades can alter transcription of key biosynthetic enzymes, thereby changing the concentration of phenolic compounds, alkaloids, and nitrogen-containing derivatives such as amide metabolites.[10]

Developmental stage also contributes significantly to metabolite distribution. Young tissues, reproductive organs, and seed coats frequently exhibit elevated concentrations of defensive secondary metabolites, reflecting the higher vulnerability of these tissues to environmental threats. Such developmental regulation ensures optimal allocation of metabolic resources toward tissues requiring the greatest chemical protection.

Table 2 represents Major classes of amide-containing plant secondary metabolites and their biological functions in plant defense, signaling, and environmental adaptation.

Table 2: Biological Functions of Amide-Containing Secondary Metabolites in Plants.

Amide class	Representative compounds	Plant source examples	Primary biological role in plant	Mechanism of action	Supporting references
Alkamides	Spilanthol, pellitorine, sanshool derivatives	*Acmella oleracea*, *Echinacea purpurea*, *Zanthoxylum* spp.	Defence against herbivores and insects	Neuroactive feeding deterrents; membrane interaction causing sensory irritation	[7,8]
Phenolic acid amides (hydroxycinnamic	Feruloyltyramine, p-coumaroylputrescine	*Nicotiana tabacum*, *Capsicum*	Pathogen resistance; cell wall	Rapid accumulation at infection sites; lignin reinforcement and	[9,11]

acid amides)		*annuum*, cereals	strengthening	antimicrobial activity	
Benzylamides/ aromatic amides	Capsaicin, dihydrocapsaicin	*Capsicum* species	Anti-fungal and anti-herbivore protection	Irritant molecules inhibiting microbial growth and animal feeding	[9,12]
Jasmonate-derived amide conjugates	Jasmonoyl-isoleucine (JA-Ile)	Widely distributed in higher plants	Stress signalling and defence gene activation	Hormone–receptor mediated transcriptional activation of defence pathways	[14]
Polyamine-derived amides	Caffeoylputrescine, feruloylputrescine	Tobacco, tomato, barley	Abiotic stress tolerance and wound response	Reactive oxygen modulation and membrane stabilization	[10,11]
Glucosinolate-related amide derivatives	Indole-based amide breakdown products	Brassicaceae family	Protection against insects and pathogens	Enzymatic hydrolysis generating toxic defensive metabolites	[8,9]

4. Pharmacological Activities of Plant-Derived Amide Compounds

Plant-derived amide metabolites exert their pharmacological effects through multi-target molecular mechanisms involving inflammatory signalling pathways, oxidative stress modulation, antimicrobial interactions, and apoptosis regulation. These integrated therapeutic mechanisms are illustrated in **Figure 4**.

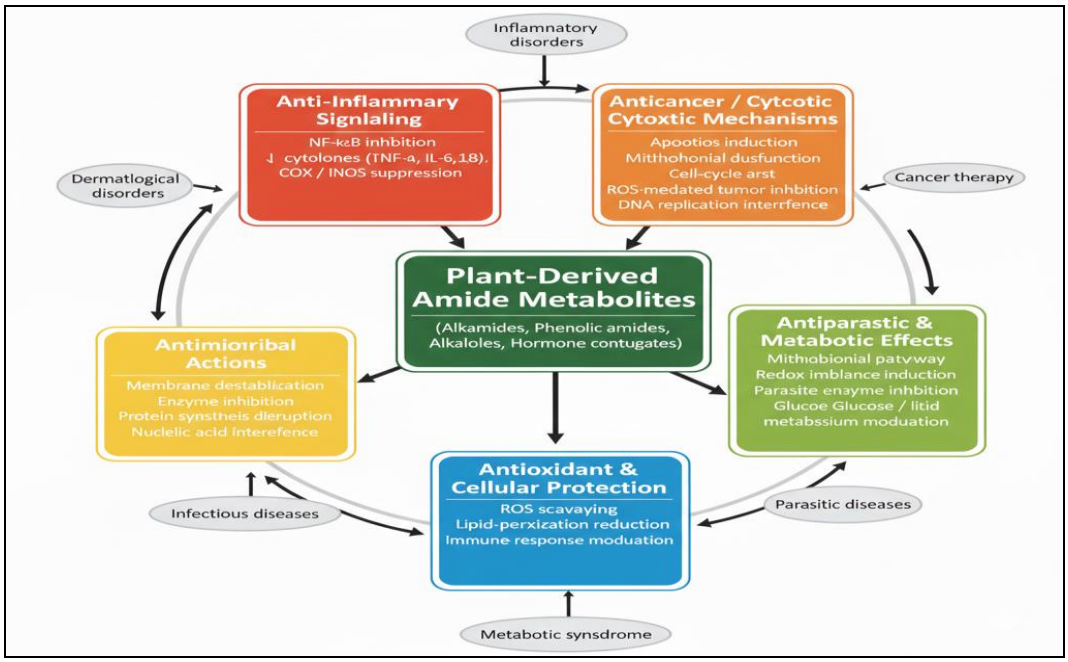

Figure 4: Pharmacological Mechanisms of Plant-Derived Amide Metabolites in Human Disease.

4.1 Anti-Inflammatory Activity

Multiple natural amide metabolites demonstrate strong anti-inflammatory effects through modulation of cytokine pathways, enzyme inhibition, and oxidative stress regulation.[16,17]

These compounds have been reported to suppress key inflammatory mediators including TNF-α, IL-1β, IL-6, cyclooxygenase (COX), and inducible nitric oxide synthase (iNOS). Several plant-derived alkamides and phenolic acid amides additionally interfere with NF-κB and MAPK signalling pathways, thereby reducing transcription of pro-inflammatory genes. Their combined antioxidant and immunomodulatory properties further enhance their therapeutic relevance, particularly for chronic inflammatory disorders where multi-target modulation is desirable.

4.2 Cytotoxic and Anticancer Properties

Cytotoxic amide derivatives isolated from plant-associated microbial systems and natural sources demonstrate potential anticancer properties and highlight the importance of these compounds as drug leads.[18] Reported mechanisms include induction of apoptosis, disruption of mitochondrial membrane potential, inhibition of DNA replication, and modulation of cell-cycle regulatory proteins.

Certain aromatic amides and polyamine-derived amide metabolites also exhibit selective toxicity toward malignant cells while showing comparatively reduced effects on normal tissues, suggesting potential for improved therapeutic indices. These findings support continued exploration of plant amide metabolites as structural templates for semi-synthetic anticancer agents and targeted chemotherapeutic development.

4.3 Antimicrobial and Protective Effects

Plant metabolites, including amide-containing compounds, exhibit antimicrobial activity and contribute to the development of therapeutic agents against resistant pathogens.[6] These molecules display activity against bacteria, fungi, and occasionally viral systems through mechanisms such as membrane destabilization, enzyme inhibition, and interference with nucleic acid synthesis.

In plants, such compounds function as phytoanticipins or inducible phytoalexins, while in pharmacological contexts they represent promising scaffolds for addressing antimicrobial resistance. Their structural diversity and natural evolutionary optimization often allow

interaction with multiple microbial targets, reducing the likelihood of rapid resistance development.

4.4 Antiparasitic and Metabolic Activities

Natural products continue to provide promising leads for antiparasitic drug development, and nitrogen-containing scaffolds including amide derivatives are increasingly explored for such applications.[20] Several plant-derived amides have demonstrated inhibitory activity against protozoan parasites through disruption of mitochondrial metabolism, interference with redox homeostasis, or inhibition of essential biosynthetic enzymes.

In addition to antiparasitic potential, emerging studies indicate that certain plant amides may influence metabolic regulation, including modulation of glucose utilization, lipid metabolism, and oxidative stress pathways. These observations broaden the therapeutic scope of plant-derived amides beyond classical antimicrobial indications.

Several plant-derived amide metabolites have progressed into clinical use or advanced drug-lead status (**Table 3**), demonstrating the translational utility of amide scaffolds originating from plant secondary metabolism.

Table 3. Major plant-derived amide compounds with clinical applications or advanced drug-lead status. This table highlights natural amide scaffolds that have been developed into therapeutics or are actively pursued as pharmacological leads, illustrating the translational value of plant secondary amide metabolites.

Table 3: Major Plant-Derived Amide Drugs and Advanced Clinical Leads.

Compound	Plant source	Amide class	Clinical / pharmacological use	Development status	References
Capsaicin	*Capsicum annuum* and related *Capsicum* spp.	Vanillyl fatty-acid amide	Topical analgesic for neuropathic pain; anti-inflammatory	Approved drug ingredient in clinical formulations	[6,13]
Piperine	*Piper nigrum*, *Piper longum*	Piperidine alkaloid amide	Bioavailability enhancer; anti-inflammatory; antimicrobial; anticancer research	Clinically used nutraceutical / pharmacological lead	[16,20]
Piperlongumine	*Piper longum*	Amide alkaloid	Selective anticancer	Advanced preclinical drug lead	[16,20]

			activity; ROS-mediated tumor inhibition		
Avenanthramides	*Avena sativa* (oat)	Phenolic acid amides	Anti-inflammatory dermatological agent; antioxidant	Used in therapeutic skin preparations and nutraceuticals	[13,19]
Feruloyltyramine derivatives	Widely distributed (e.g., tobacco, cereals, tomato)	Hydroxycinnamic acid amides	Antimicrobial defense compounds with pharmaceutical potential	Experimental pharmacological leads	[11,13]
Aurantiamide derivatives	Various medicinal plants	Aromatic peptide-like amides	Reported anti-inflammatory and anticancer activities	Investigational natural-product scaffold	[18,19]

5. Drug Discovery Potential

Natural products remain central to modern drug development, providing structurally complex scaffolds that frequently outperform synthetic screening libraries in biological relevance.[3,5]

Their evolutionary selection for biological interaction often results in enhanced target specificity and favourable pharmacophore architecture.

The amide functional group is particularly attractive in medicinal chemistry because of:

- high metabolic stability
- hydrogen-bond donor/acceptor capacity
- conformational control
- strong protein-binding compatibility

These characteristics allow amide-containing molecules to participate in stable ligand–receptor interactions and predictable pharmacokinetic behaviour, making them valuable motifs in rational drug design.

Integration of ethnobotanical knowledge, metabolomics, and multi-omics discovery strategies has significantly accelerated identification of new plant-derived drug leads.[19] High-resolution mass spectrometry, genome-guided metabolite discovery, and pathway engineering now permit systematic exploration of previously inaccessible natural products. Artificial intelligence-driven screening and predictive modelling further enable rapid prioritization of

promising natural compounds for pharmacological investigation.[21,22] reducing time and cost associated with conventional discovery pipelines.

6. Challenges and Future Perspectives

Despite their promise, several challenges hinder development of plant-derived amide metabolites:

- variability in phytochemical composition
- limited availability of rare plant species
- insufficient structural characterization
- lack of systematic SAR studies
- need for improved standardization of medicinal plant materials.[23]

Additional obstacles include difficulties in large-scale isolation, seasonal variation in metabolite abundance, and incomplete understanding of biosynthetic pathways. Furthermore, translation from in vitro activity to clinical efficacy remains limited for many natural products due to bioavailability and toxicity considerations.

Future progress will require integrated approaches combining phytochemistry, biosynthesis studies, computational drug design, and synthetic modification strategies. Advances in synthetic biology, metabolic engineering, and sustainable cultivation techniques are expected to improve access to rare plant metabolites and enable scalable production of pharmacologically important amide compounds.

7. CONCLUSION

Amide-containing secondary metabolites represent an important and biologically versatile class of natural products widely distributed in medicinal plants and associated microbial systems. Their participation in plant defence, stress signalling, and metabolic regulation, together with their diverse pharmacological properties, highlights their significance as promising scaffolds for future therapeutic development.

Ongoing advances in analytical chemistry, molecular biology, metabolomics, and computational drug discovery are expected to substantially expand the catalogue of known plant amide metabolites and clarify their mechanisms of biological action. Continued interdisciplinary exploration of plant-derived amide metabolites using modern analytical,

computational, and synthetic approaches is therefore likely to yield valuable leads for next-generation therapeutic agents and innovative drug discovery strategies.

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