World Journal of Biology Pharmacy and Health Sciences
eISSN: 2582-5542
Cross Ref DOI: 10.30574/wjbphs
Journal homepage: https://wjbphs.com/

(Review Article)

Check for updates

Unveiling the phytochemical tapestry of delonix regia: A comprehensive review of its chemical constituents and phytochemistry

Arshin Solomon *, Pragya Pandey, Meghna Singh, Arnab Roy, Kshitiz Patel and Dolly Tiwari

Kalinga University, Kotni, Atal Nagar-Nava Raipur, Chhattisgarh 492101, India.

World Journal of Biology Pharmacy and Health Sciences, 2025, 21(01), 707-722

Publication history: Received on 16 December 2024; revised on 27 January 2025; accepted on 30 January 2025

Article DOI: https://doi.org/10.30574/wjbphs.2025.21.1.0103

Abstract

Delonix regia, commonly known as Royal Poinciana, is a widely recognized ornamental tree with significant ethnomedicinal value. Its diverse phytochemical composition includes flavonoids, alkaloids, tannins, phenolic compounds, and terpenoids, which exhibit a range of biological activities. The flowers, rich in quercetin and kaempferol derivatives, demonstrate strong antioxidant and anti-inflammatory effects. The bark contains alkaloids, such as β-sitosterol, which has shown anti-inflammatory and antimicrobial properties. Furthermore, phenolic compounds like gallic and ellagic acid enhance the plant's defence mechanisms and oxidative stress responses. Studies have revealed that the seed pods and leaves possess unique phytosterols and tannins that contribute to their hepatoprotective and antimicrobial properties. The ecological role of *D. regia* adds toits significance, as it supports local biodiversity and helps regulate microclimates. The tree's bioactive compounds also hold promise for various pharmaceutical applications, including antioxidant, anti-inflammatory, and antimicrobial therapies. Recent investigations into the structure-activity relationships of these compounds have shed light on their molecular mechanisms, suggesting potential for therapeutic development. Future research may focus on elucidating these mechanisms, optimizing extraction methods, and exploring sustainable uses for this remarkable species in medicine and biotechnology. *Delonix regia* thus represents a compelling subject for further pharmaceutical and ecological studies.

Keywords: *Delonix regia*; Flavonoids; Alkaloids; Antioxidant; Anti-inflammatory; Antimicrobial

1. Introduction

Figure 1 Flowering plant of D. regia

* Corresponding author: Arshin Solomon

The ornamental tree Delonix regia, a member of the diverse Fabaceae family, has emerged as a fascinating subject in ethnomedicinal (1) research, with its applications spanning across tropical and subtropical zones worldwide. This majestic species, commonly known as the Royal Poinciana or Flame Tree, presents a remarkable dichotomy between its stunning aesthetic appeal and its profound medicinal potential. The tree's most striking feature – its brilliant crimson flowers (2,3) that create a canopy of fire-like blooms – serves as nature's billboard for the complex biochemical laboratory operating within its tissues. The intricate phytochemical profile of D. regia encompasses a wide array of bioactive compounds, including flavonoids, alkaloids, tannins, steroids, and terpenoids (4,5). These compounds work in concert to produce various therapeutic effects that traditional healers have utilized for

generations. The bark, particularly rich in tannins, has demonstrated significant antimicrobial properties, while the leaves contain unique flavonoid glycosides that contribute to anti-inflammatory(6,7) responses. Modern scientific investigation has begun t to unravel the molecular mechanisms underlying these traditional applications. Sophisticated analytical techniques have revealed that the flower extracts contain anthocyanins and other polyphenolic compounds that exhibit notable antioxidant activity. (8,9) These compounds effectively neutralize free radicals, potentially offering protection against oxidative stress-related conditions. The roots, often overlooked in casual observation, harbor betasitosterol and other phytosterols that have shown promising results in managing various metabolic disorders (10,11). The tree's seed pods, which hang like giant ornamental pendants, contain compounds that have demonstrated hepatoprotective properties in preliminary studies. The seeds themselves are repositories of unique proteins and essential oils that have attracted attention for their potential applications in both pharmaceutical and industrial sectors. Recent research has also highlighted the presence of novel peptides in the seed coat that exhibit remarkable antimicrobial properties against several pathogenic organisms.(12,13) Beyond its chemical constituents, D. regia's ecological role adds another layer to its significance. The tree serves as a crucial habitat for various pollinators, particularly during its flowering season, contributing to local biodiversity. Its extensive root system helps prevent soil erosion, while its broad canopy provides natural shade in urban landscapes, contributing to microclimate regulation(14,15). The intersection of traditional knowledge and modern scientific investigation continues tounveil new aspects of this remarkable species. Each part of the tree – from its deep-reaching roots to its towering canopy – represents a potential source of bioactive compounds waiting to be fully characterized and understood. This ongoing research not only validates traditional medicinal applications but also points toward new therapeutic possibilities, making D. regia a compelling subject for future pharmaceutical development and sustainable resource utilization.(16,17)

2. Chemical Composition

2.1. Flavonoids

The floral matrix of Delonix regia, commonly known as the Royal Poinciana or Flamboyant tree, harbors a sophisticated network of flavonoid compounds that form the cornerstone of its phytochemical profile. (18,19) Through advanced chromatographic techniques and spectroscopic analyses, researchers have identified several distinct classes of flavonoids(20) that contribute to the plant's remarkable therapeutic properties.

Quercetin and its glycosidic derivatives represent a predominant class of flavonoids within the flower extracts. These compounds feature a characteristic 3,5,7,3',4'pentahydroxyflavone skeleton, with various sugar moieties (21,22) attached at specific positions. The presence of O-glycosidic bonds, particularly at the C-3 and C-7 positions, enhances the compound's solubility and bioavailability in physiological systems. (23,24) These structural modifications play a crucial role in determining the compound's absorption and distribution within biological systems.

Kaempferol derivatives constitute another significant group of flavonoids identified in D. regia flowers. These compounds share a 3,5,7,4'-tetrahydroxyflavone basic structure, with various substitution patterns that influence their biological activities. The presence of hydroxyl groups at specific positions enables these molecules to act as powerful electron donors, contributing to their antioxidant capabilities through free radical scavenging mechanisms. (25,26)

Apigenin, a flavone with a 5,7,4'-trihydroxyflavone structure, has been isolated and characterized from the flower extracts. This compound demonstrates remarkable stability under physiological conditions and exhibits various biological activities, including anti-inflammatory and antioxidant properties (27,28). The planar structure of apigenin facilitates its interaction with cellular targets, enhancing its therapeutic potential. (29,30)

Leucocyanidin, belonging to the flavan-3,4-diol class, represents a unique flavonoid component in D. regia flowers. This compound serves as a crucial intermediate in the biosynthesis of condensed tannins and contributes to the plant's defense mechanisms (31,32). The presence of hydroxyl groups at the C-3 and C-4 positions provides distinct chemical properties that influence its biological activities. (33)

The synergistic interactions between these flavonoid compounds are particularly noteworthy. Spectroscopic analyses have revealed that these molecules often exist in complex associations with sugar moieties, forming glycosidic conjugates (34,35). These structural modifications significantly influence their physicochemical properties, including solubility, stability, and bioavailability.(36,37) The glycosylation patterns observed in D. regia flavonoids enhance their absorption in biological systems and contribute to their therapeutic efficacy through improved pharmacokinetic properties.(38,39)

2.2. Alkaloids

Alkaloids represent a significant class of bioactive compounds found within the bark and leaves of this species. The presence of β-sitosterol, a phytosterol with a characteristic steroid nucleus, plays a crucial role in the plant's cellular membrane composition(40, 41) and contributes to its medicinal properties. Research has demonstrated that β-sitosterol exhibits notable anti-inflammatory effects by modulating key inflammatory mediators and cytokine production pathways. (42,43) Leucocyanidin, belonging to the flavonoid family, exists in both the bark and leaf tissues. This compound's molecular structure features a distinctive flavan nucleus with hydroxyl group substitutions, enabling it to function as a powerful antioxidant.(44,45) Through electron donation mechanisms, leucocyanidin effectively neutralizes harmful free radicals, thereby protecting cellular components from oxidative damage.(46,47)

The presence of hordenine derivatives adds another layer of pharmacological significance. These phenethylamine alkaloids, structurally related to neurotransmitters, demonstrate fascinating bioactive properties.(48,49) The plant synthesizes various hordenine based compounds through complex biosynthetic pathways involving tyrosine as a precursor. These derivatives exhibit varied biological activities, including antimicrobial effects against both gram-positive and gram-negative bacteria, potentially through membrane disruption mechanisms.(50,51)

The steroid and triterpene content represents a diverse group of secondary metabolites with complex carbon frameworks. These compounds are synthesized via the mevalonate pathway, incorporating multiple isoprene units (52, 53) to form their characteristic structures. The steroids present include various derivatives with modifications to their basic cyclopentanoperhydrophenanthrene nucleus, while the triterpenes typically contain six isoprene units arranged in specific spatial configurations. (54, 55)

The pharmacological activities of these alkaloids work through multiple mechanisms of action. Their antimicrobial properties involve disruption of bacterial cell membranes, interference with protein synthesis, and modulation of bacterial efflux pumps.(56,57) The antiinflammatory effects are mediated through various pathways, including inhibition of prostaglandin synthesis, reduction of pro-inflammatory cytokine production, and modulation of immune cell function.(58,59)

Recent studies have begun to elucidate the structure-activity relationships of these compounds, revealing how specific molecular features contribute to their biological effects. The presence of particular functional groups, stereochemistry, and molecular flexibility all play crucial roles in determining their interaction with cellular targets (60, 61) and subsequent therapeutic outcomes.

The synergistic interactions between these various alkaloids likely contribute to the overall medicinal properties of the plant, creating a complex network of biological activities that cannot be attributed to single compounds in isolation. (62)

2.3. Phenolic Compounds

Phenolic compounds represent one of the most diverse and widespread groups of secondary metabolites in the plant kingdom. These organic compounds are characterized by the presence of one or more hydroxyl groups (-OH) attached directly to aromatic hydrocarbon rings.(63,64) The four major phenolic acids highlighted – gallic acid, ellagic acid, tannic acid, and protocatechuic acid(65,66) – serve crucial roles in plant defense mechanisms, growth regulation, and ecological interactions(67).

Gallic acid (3,4,5-trihydroxybenzoic acid) functions as a key precursor molecule in the biosynthesis of hydrolyzable tannins.(68) In plant tissues, it exhibits potent antioxidant properties by scavenging free radicals and chelating metal ions, thereby protecting cellular components from oxidative damage. Its concentration tends to peak during periods of environmental stress, suggesting an adaptive response mechanism. (69, 70)

Ellagic acid, a dimeric derivative of gallic acid, predominantly occurs in woody tissues and fruit seeds. Its molecular structure, featuring four hydroxyl groups and two lactone rings, enables strong protein-binding capabilities (71, 72). Plants often accumulate higher levels of ellagic acid during fruit ripening and in response to pathogen attacks, indicating its role in both developmental processes and defense strategies.

Tannic acid, a complex polyphenolic compound, belongs to the hydrolyzable tannin family. Its molecular architecture consists of multiple galloyl units esterified to a glucose core, creating a large molecule with remarkable protein-precipitation properties.(73,74) The synthesis and accumulation of tannic acid show distinct patterns influenced by factors such as soil composition, altitude, and seasonal variations in temperature and rainfall.(75,76)

Protocatechuic acid (3,4-dihydroxybenzoic acid), while structurally simpler than the other compounds, plays vital roles in plant stress responses and cell wall lignification. Its biosynthesis involves the shikimate pathway, and its production often correlates with exposure to UV radiation and drought conditions. (77, 78)

The geographical and seasonal variations in these phenolic compounds reflect the remarkable plasticity of plant secondary metabolism. For instance, plants growing at higher altitudes typically show elevated levels of these compounds, particularly during periods of intense UV exposure. Seasonal fluctuations often follow predictable patterns, with concentrations generally peaking during periods of environmental stress (79, 80) or as part of developmental programs.

The environmental modulation of these compounds occurs through complex signaling networks involving phytohormones, transcription factors, and epigenetic modifications. (81, 82) Factors such as soil pH, mineral availability, temperature regimes, and precipitation patterns can significantly influence the biosynthetic pathways responsible for phenolic compound production (83, 84). This environmental responsiveness allows plants to optimize their resource allocation and defensive capabilities according to prevailing conditions. (85)

Understanding these variations has significant implications for both basic research in plant biology and applied fields such as pharmaceutical development and agricultural optimization, as the timing of harvest and growth conditions can substantially impact the yield of these valuable compounds.

Table 1 Phytochemical Composition of *Delonix regia*: A Summary of Key Bioactive Compounds

Phytochemical Class	**Compound**	**Structure**	**Biological Activity**
Flavonoids	Quercetin	3,5,7,3',4'-pentahydroxyflavone	Antioxidant, Bioavailability via O-glycosidic bonds
	Kaempferol	3,5,7,4'-tetrahydroxyflavone	Free Radical Scavenging, Antioxidant
	Apigenin	5,7,4'-trihydroxyflavone	Anti-inflammatory, Antioxidant
	Leucocyanidin	Flavan-3,4-diol	Intermediate in Tannin Biosynthesis, Antioxidant
Alkaloids	β-Sitosterol	Steroid nucleus	Anti-inflammatory, Membrane Composition Modulation
	Hordenine Derivatives	Phenethylamine	Antimicrobial, Membrane Disruption
Phenolic Compounds	Gallic Acid	3,4,5-trihydroxybenzoic acid	Antioxidant, Metal Chelation
	Ellagic Acid	Dimer of Gallic Acid	Protein Binding, Defense Response
	Tannic Acid	Galloyl units esterified to glucose	Protein Precipitation, Stress Response
	Protocatechuic Acid	3,4-dihydroxybenzoic acid	Cell Wall Lignification, Stress Response

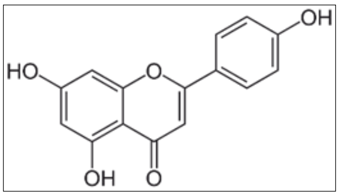	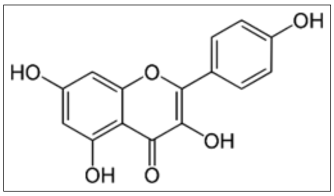	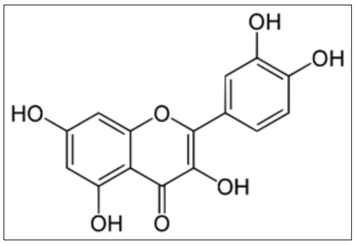
Figure 2 Structure of Quercetin	**Figure 3** Structure of Kaempferol	**Figure 4** Structure of Kaempferol
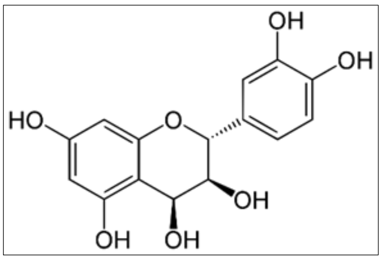	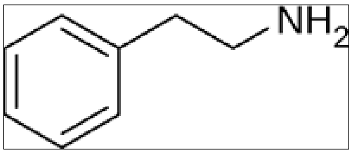	
Figure 5 Structure of Leucocyanidin	**Figure 6** Structure of Phenethylamine	

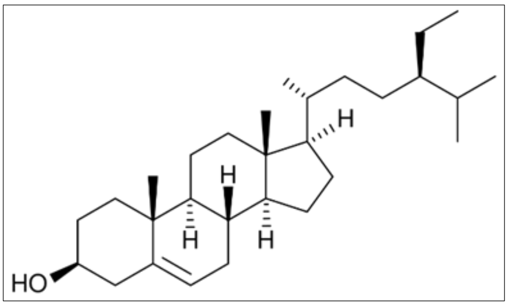	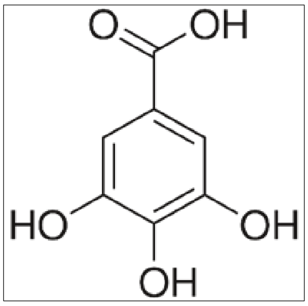
Figure 7 Structure of β-Sitosterol	**Figure 8** Structure of Gallic Acid
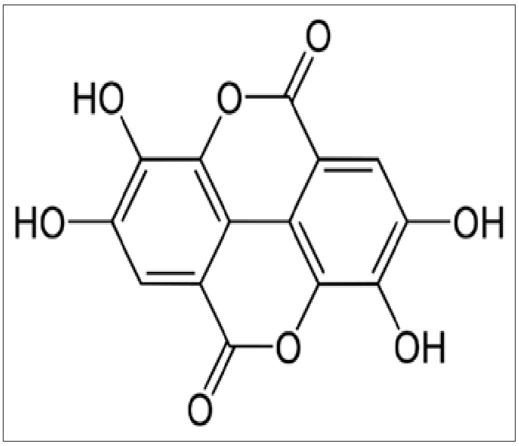	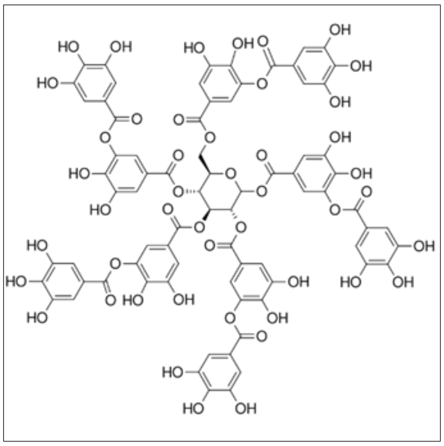
Figure 9 Structure of Ellagic Acid	**Figure 10** Structure of Tannic Acid

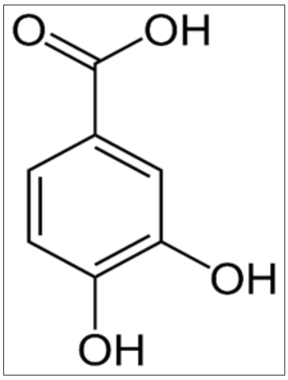

Figure 11 Structure of Protocatechuic Acid

2.4. Distribution of Phytochemicals across Plant Parts

2.4.1. Flowers

The intricate biochemistry of flowers reveals a fascinating array of compounds that contribute to their visual allure and biological functions. At the molecular level, these delicate structures house an impressive variety of bioactive substances that serve multiple purposes in plant survival and reproduction (86, 87).

Anthocyanins, the primary architects of red coloration in flowers, belong to the flavonoid (88) family of compounds. These water-soluble pigments accumulate in the vacuoles of petal cells, where their chemical structure allows them to absorb specific wavelengths of light, resulting in the vivid red hues that attract pollinators (89, 90). The intensity of red coloration varies based on factors such as vacuolar pH, the presence of co-pigments, and metal ion complexation. Under acidic conditions, anthocyanins typically appear more intensely red, while alkaline conditions (91, 92) can shift their colour toward purple or blue. The flowers' rich carotenoid content adds another layer of complexity to their chemical makeup. These lipid-soluble compounds primarily occur in chromoplasts, where they form crystalline structures or exist in oil droplets (93, 94). Beyond their role in producing yellow, orange, and sometimes red colours, carotenoids serve as essential photoprotective agents, helping shield the flower's delicate tissues from excessive light damage (95). They also act as precursors for various plant hormones and contribute to the production of volatile compounds that attract specific pollinators. The essential oils present in the flowers consist predominantly of terpenes, which are assembled from five-carbon isoprene units (96, 97) through complex biosynthetic pathways. These volatile compounds create distinctive floral scents that serve multiple ecological functions. Some terpenes act as attractants for beneficial insects, while others may deter herbivores or protect against pathogenic microorganisms (98, 99). The composition of these essential oils often varies throughout the day, responding to environmental conditions and the activity patterns of potential pollinators. Phenolic glycosides represent another significant class of compounds in the flowers. These molecules consist of phenolic compounds chemically bound to sugar moieties, creating structures that contribute to both flower defence and pigmentation.(100,101) Some phenolic glycosides serve as chemical deterrents against herbivores, while others function as UV-absorbing compounds, protecting sensitive floral tissues from radiation damage. These compounds also play roles in flower development and stress response mechanisms **(102, 103).** The intricate interplay between these various compounds creates a dynamic chemical environment within the flower tissues. Environmental factors such as temperature, light intensity, and soil composition can influence the synthesis and accumulation of these compounds, leading to variations in flower colour, scent, and defensive capabilities **(104,105).** This chemical complexity not only ensures the survival and reproductive success of the plant but also contributes to the remarkable diversity of floral characteristics observed in nature.

2.4.2. Leaves

The phytochemical profile of leaves reveals an impressive array of secondary metabolites. Hydrolyzable and condensed tannins exist in varying proportions, contributing to plant defense mechanisms and exhibiting potential therapeutic properties.(106,107) The presence of diverse saponin glycosides, characterized by their amphipathic nature, suggests evolutionary adaptations for herbivore deterrence. Terpenoids, particularly mono- and sesquiterpenes, contribute to the aromatic properties while serving crucial ecological functions in plant-insect interactions (108,109). Steroidal compounds, including β-sitosterol and stigmasterol, play vital roles in membrane fluidity and cellular signaling pathways. (110,111) The internal anatomy demonstrates remarkable organizational complexity. The mesophyll tissue differentiates into palisade and spongy layers, optimizing light capture and gas exchange efficiency (112). Vascular bundles, encased in bundle sheath cells, facilitate precise control over water and solute transport. Specialized idioblasts containing calcium oxalate crystals serve both structural and defensive functions. (113, 114)

Leaves execute sophisticated metabolic processes beyond photosynthesis. Complex enzyme systems regulate the synthesis and degradation of primary and secondary metabolites (115,116). The presence of various phenolic compounds indicates advanced oxidative stress response mechanisms. Protein-protein interactions within chloroplasts orchestrate light-harvesting complexes, while specialized transport proteins facilitate nutrient mobilization across cellular compartments. (117, 118)

2.4.3. Bark Components

The bark tissue exhibits a sophisticated chemical architecture that reflects it's protective and transport functions. The high alkaloid content, comprising both indole and isoquinoline derivatives, represents a sophisticated chemical defense mechanism against herbivores and pathogens (119,120). Procyanidins, belonging to the proanthocyanidin class of polyphenols, demonstrate significant antioxidant properties and contribute to the bark's structural integrity. Beta-sitosterol, a prominent phytosterol, plays vital roles in membrane organization and cellular signalling (121,122). Lupeol, a pentacyclic triterpene, exhibits remarkable biological activities, including anti-inflammatory and anticancer properties, highlighting the bark's potential(123,124) pharmaceutical significance.

2.4.4. Composition of Seeds

Seed composition reveals a complex array of biologically active compounds essential for plant reproduction and survival. The protein content, characterized by a balanced amino acid profile, provides essential nutrients for embryonic development (125,126). Essential fatty acids, particularly omega-3 and omega-6 polyunsaturated fatty acids, serve as energy reserves and contribute to membrane structure (127,128). Galactomannans, complex polysaccharides with unique rheological properties, function as energy storage compounds and play crucial roles in seed hydration mechanisms (129,130). Protease inhibitors represent sophisticated defensive molecules that protect seed proteins from premature degradation and defend against pathogenic organisms (131,132).

Table 2 Distribution of Key Phytochemicals across Plant Parts: Flowers, Leaves, Bark, and Seeds

Plant Part	Key Phytochemicals	Functions	Unique Characteristics
Flowers	Anthocyanins, Carotenoids, Essential Oils, Phenolic Glycosides	Attract pollinators, UV protection, tissue defense, hormone precursors	Anthocyanins contribute to vivid red hues influenced by pH; carotenoids provide photoprotection and coloration. Essential oils vary diurnally for ecological functions.
Leaves	Tannins, Saponin Glycosides, Terpenoids, Steroidal Compounds	Defense against herbivores, oxidative stress response, signaling, structural integrity	Mesophyll tissue specialization optimizes photosynthesis. Idioblasts containing calcium oxalate crystals add to defense.
Bark	Alkaloids, Procyanidins, Beta-Sitosterol, Lupeol	Structural integrity, antioxidant defense, anti-inflammatory and anticancer properties	Alkaloids (indole, isoquinoline) as advanced chemical defense. Lupeol highlights pharmaceutical potential.
Seeds	Proteins, Essential Fatty Acids, Galactomannans, Protease Inhibitors	Nutrient storage, energy reserves, defense against degradation and pathogens	Galactomannans ensure seed hydration; protease inhibitors prevent premature protein breakdown.

3. Physiological Functions and Ecological Implications

These diverse chemical constituents collectively contribute to the plant's survival, reproduction, and ecological interactions. The distribution and concentration of these compounds often vary seasonally and in response to environmental stressors, demonstrating the plant's remarkable adaptive capabilities. The presence of these bioactive compounds also influences plant-microbe interactions, soil chemistry, and ecosystem dynamics, highlighting their broader ecological significance (133,134).

4. Potential Applications and Future Research Directions

The complex chemical profiles of these plant tissues suggest numerous potential applications in pharmaceuticals, agriculture, and biotechnology. Understanding the biosynthetic pathways and regulation of these compounds opens new avenues for metabolic engineering and crop improvement (135,136). Future research directions may focus on elucidating the precise mechanisms of action, exploring synergistic interactions between different compounds, and developing sustainable extraction methods for valuable bioactive components. (137,138)

5. Molecular Mechanisms and Cellular Integration

At the cellular level, these compounds participate in intricate signaling networks and metabolic pathways. Their synthesis, transport, and accumulation involve sophisticated regulatory mechanisms (139,140) that respond to both internal and external cues. Understanding these molecular interactions provides insights into plant adaptation and evolution, while also revealing potential targets for therapeutic interventions and biotechnological applications. This comprehensive analysis demonstrates the remarkable complexity and diversity of plant tissue (141,142). Phytochemistry, emphasizing both its fundamental biological significance and potential practical applications. The integration of traditional knowledge with modern analytical techniques continues to reveal new aspects of these fascinating chemical systems, promising exciting developments in various fields of science and technology.

6. Biological Activities of Major Compounds in Delonix regia

6.1. Antioxidant Properties

The antioxidant potential of *Delonix regia*, commonly referred to as Royal Poinciana or Gulmohar, is attributed to its high content of flavonoids and phenolic compounds. These phytochemicals exhibit significant free radical scavenging activity, as demonstrated by their ability to neutralize reactive oxygen species (ROS) effectively. Comparative studies reveal that the plant's antioxidant properties rival those of standard antioxidants like ascorbic acid and quercetin, with remarkably low IC50 values indicating strong efficacy. The flavonoid components, such as quercetin and kaempferol derivatives, contribute significantly to these effects due to their ability to donate electrons and stabilize free radicals. Phenolic acids like gallic acid and protocatechuic acid further enhance this activity by chelating metal ions and protecting cellular structures from oxidative damage. This robust antioxidant profile underscores the therapeutic potential of D. regia in mitigating oxidative stress and preventing related disorders such as neurodegeneration, cardiovascular diseases, and cancer (143-145).

6.2. Antimicrobial Activity

Delonix regia extracts exhibit broad-spectrum antimicrobial activity, effectively targeting both gram-positive and gram-negative bacteria. This activity is primarily attributed to the presence of alkaloids, phenolic compounds, and other secondary metabolites. Specific constituents, such as hordenine derivatives and β-sitosterol, disrupt bacterial cell membranes and interfere with protein synthesis pathways, thereby inhibiting microbial growth. Additionally, phenolic acids like tannic acid exhibit protein-precipitation properties, further contributing to antimicrobial efficacy. Studies suggest that these mechanisms collectively enable *D. regia* to combat diverse microbial strains, supporting its traditional use in treating infections. The potential of this plant to serve as a source for novel antimicrobial agents has garnered significant attention in pharmaceutical research, especially in the context of rising antibiotic resistance (146-148).

6.3. Anti-inflammatory Effects

The anti-inflammatory properties of *Delonix regia* are attributed to its rich triterpene and flavonoid content. These bioactive compounds modulate various inflammatory pathways, resulting in the suppression of pro-inflammatory mediators such as cytokines and prostaglandins. Flavonoids like apigenin and quercetin derivatives exert their effects by inhibiting the cyclooxygenase (COX) enzymes and reducing the production of reactive nitrogen species (RNS), thereby mitigating inflammation. Triterpenes enhance these effects by stabilizing cellular membranes and reducing vascular permeability. Experimental studies have demonstrated that *D. regia* extracts significantly alleviate inflammation in animal models, validating its traditional applications in treating inflammatory conditions. These findings highlight the potential of *D. regia* as a natural anti-inflammatory agent and support its further exploration in therapeutic development for conditions such as arthritis, asthma, and inflammatory bowel disease (149-152).

Table 3 Biological Activities and Bioactive Compounds of *Delonix regia*

Activity	**Major Bioactive Compounds**	**Mechanism of Action**	**Therapeutic Implications**
Antioxidant	Flavonoids (quercetin, kaempferol derivatives), phenolic acids (gallic acid, protocatechuic acid)	Scavenges free radicals, stabilizes ROS, chelates metal ions, protects cellular structures	Neurodegeneration, cardiovascular diseases, cancer prevention
Antimicrobial	Alkaloids, hordenine derivatives, β-sitosterol, phenolic acids (tannic acid)	Disrupts bacterial membranes, interferes with protein synthesis, precipitates microbial proteins	Treatment of bacterial infections, combating antibiotic resistance
Anti-inflammatory	Flavonoids (apigenin, quercetin derivatives), triterpenes	Inhibits COX enzymes, suppresses pro-inflammatory mediators (cytokines, prostaglandins), stabilizes cellular membranes	Arthritis, asthma, inflammatory bowel disease

7. Conclusion

The comprehensive exploration of *Delonix regia* highlights its multifaceted potential as a source of bioactive compounds with significant pharmacological and ecological importance. This tree, revered for its ornamental appeal, emerges as a reservoir of diverse phytochemicals, including flavonoids, alkaloids, tannins, steroids, and phenolic compounds. The structural complexity and synergistic interactions among these compounds underline the plant's robust antioxidant, anti-inflammatory, and antimicrobial activities, aligning with its historical ethnomedicinal applications. Each plant part—flowers, leaves, bark, and seeds—contributes uniquely toits therapeutic profile, offering a plethora of bioactive constituents that could serve as templates for pharmaceutical innovation. From a biochemical perspective, the flavonoids in D. regia demonstrate pronounced antioxidant and anti-inflammatory potential through mechanisms involving free radical scavenging and modulation of inflammatory pathways. The alkaloids, phenolic acids, and essential oils identified across the plant exhibit antimicrobial properties, underscoring their value in combating pathogenic microorganisms. Phenolic compounds such as gallic acid and tannins further enhance the plant's therapeutic profile by offering protective effects against oxidative stress and contributing to anti-carcinogenic potential. The integration of these bioactive components creates a synergistic network that cannot be solely attributed to isolated compounds, emphasizing the holistic significance of this species in traditional medicine. Ecologically, *D. regia* plays a pivotal role in biodiversity conservation, soil stabilization, and microclimate regulation, reinforcing its environmental relevance. Its phytochemical adaptability to seasonal and environmental stresses highlights the dynamic nature of its secondary metabolite production, which could be leveraged for sustainable resource utilization and crop improvement. Despite the promising findings, gaps remain in fully elucidating the molecular pathways and structure-activity relationships of D. regia's constituents. Future research should focus on advanced pharmacological studies, sustainable extraction methods, and biotechnological applications to maximize its therapeutic potential. By bridging traditional knowledge with modern science, D. regia offers an inspiring model for exploring nature's chemical diversity and its applications in medicine, agriculture, and industry. Its remarkable versatility reaffirms its status as a valuable natural resource poised for impactful contributions to health and environmental sustainability.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

References

[1] Salem, M. Z., Abdel-Megeed, A., & Ali, H. M. (2014). Stem wood and bark extracts of Delonix regia (Boj. Ex. Hook): Chemical analysis and antibacterial, antifungal, and antioxidant properties. *BioResources*, *9*(2), 2382-2395.

[2] Revels, T. J. (2011). *Sunshine paradise: A history of Florida Tourism*. University Press of Florida.

[3] Smith, P. H., & Schmidt, B. (Eds.). (2007). Making knowledge in early modern Europe: practices, objects, and texts, 1400-1800. University of Chicago Press.

[4] Senguttuvan, J., Paulsamy, S., & Karthika, K. (2014). Phytochemical analysis and evaluation of leaf and root parts of the medicinal herb, Hypochaeris radicata L. for in vitro antioxidant activities. *Asian Pacific journal of tropical biomedicine*, *4*, S359-S367.

[5] Shah, S. M. A., Akram, M., Riaz, M., Munir, N., & Rasool, G. (2019). Cardioprotective potential of plant-derived molecules: a scientific and medicinal approach. *Dose-response*, *17*(2), 1559325819852243.

[6] Igbinosa, O. O., Igbinosa, E. O., & Aiyegoro, O. A. (2009). Antimicrobial activity and phytochemical screening of stem bark extracts from Jatropha curcas (Linn). *African journal of pharmacy and pharmacology*, *3*(2), 058-062.

[7] Al-Khayri, J. M., Sahana, G. R., Nagella, P., Joseph, B. V., Alessa, F. M., & Al-Mssallem, M. Q. (2022). Flavonoids as potential anti-inflammatory molecules: A review. Molecules, 27(9), 2901.

[8] Dai, J., & Mumper, R. J. (2010). Plant phenolics: extraction, analysis and their antioxidant and anticancer properties. *Molecules*, *15*(10), 7313-7352.

[9] Kong, J. M., Chia, L. S., Goh, N. K., Chia, T. F., & Brouillard, R. (2003). Analysis and biological activities of anthocyanins. *Phytochemistry*, *64*(5), 923-933.

[10] Sen, S., Chakraborty, R., Sridhar, C., Reddy, Y. S. R., & De, B. (2010). Free radicals, antioxidants, diseases and phytomedicines: current status and future prospect. *Int J Pharm Sci Rev Res*, *3*(1), 91-100.

[11] Upadhyay, S., & Dixit, M. (2015). Role of polyphenols and other phytochemicals on molecular signaling. *Oxidative medicine and cellular longevity*, *2015*(1), 504253.

[12] Anwar, F., Latif, S., Ashraf, M., & Gilani, A. H. (2007). Moringa oleifera: a food plant with multiple medicinal uses. Phytotherapy Research: An International Journal Devoted to Pharmacological and Toxicological Evaluation of Natural Product Derivatives, 21(1), 17-25.

[13] Sharifi-Rad, J., Sureda, A., Tenore, G. C., Daglia, M., Sharifi-Rad, M., Valussi, M., ... & Iriti, M. (2017). Biological activities of essential oils: From plant chemoecology to traditional healing systems. *Molecules*, *22*(1), 70.

[14] Murgueitio, E., Calle, Z., Uribe, F., Calle, A., & Solorio, B. (2011). Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. *Forest Ecology and Management*, *261*(10), 1654-1663.

[15] Archibold, O. W. (2012). *Ecology of world vegetation*. Springer Science & Business Media.

[16] Von Humboldt, A., & Bonpland, A. (2010). *Essay on the Geography of Plants*. University of Chicago Press.

[17] Kellert, S. R. (2011). Biophilic design: The theory, science and practice of bringing buildings to life. John Wiley & Sons.

[18] Modi, A., Mishra, V., Bhatt, A., Jain, A., Mansoori, M. H., Gurnany, E., & Kumar, V. (2016). Delonix regia: historic perspectives and modern phytochemical and pharmacological researches. *Chinese journal of natural medicines*, *14*(1), 31-39.

[19] Adje, F., Lozano, Y. F., Meudec, E., Lozano, P., Adima, A., N'zi, G. A., & Gaydou, E. M. (2008). Anthocyanin characterization of pilot plant water extracts of Delonix regia flowers. *Molecules*, *13*(6), 1238-1245.

[20] Mabry, T., Markham, K. R., & Thomas, M. B. (2012). *The systematic identification of flavonoids*. Springer Science & Business Media.

[21] Kumar, S., & Pandey, A. K. (2013). Chemistry and biological activities of flavonoids: an overview. *The scientific world journal*, *2013*(1), 162750.

[22] D'Andrea, G. (2015). Quercetin: A flavonol with multifaceted therapeutic applications?. *Fitoterapia*, *106*, 256-271.

[23] Gattuso, G., Barreca, D., Gargiulli, C., Leuzzi, U., & Caristi, C. (2007). Flavonoid composition of citrus juices. *Molecules*, *12*(8), 1641-1673.

[24] Wang, W., Sun, C., Mao, L., Ma, P., Liu, F., Yang, J., & Gao, Y. (2016). The biological activities, chemical stability, metabolism and delivery systems of quercetin: A review. *Trends in food science & technology*, *56*, 21-38.

[25] M Calderon-Montano, J., Burgos-Morón, E., Pérez-Guerrero, C., & López-Lázaro, M. (2011). A review on the dietary flavonoid kaempferol. *Mini reviews in medicinal chemistry*, *11*(4), 298-344.

[26] Seyoum, A., Asres, K., & El-Fiky, F. K. (2006). Structure–radical scavenging activity relationships of flavonoids. *Phytochemistry*, *67*(18), 2058-2070.

[27] Martens, S., & Mithöfer, A. (2005). Flavones and flavone synthases. *Phytochemistry*, *66*(20), 2399-2407.

[28] Abotaleb, M., Samuel, S. M., Varghese, E., Varghese, S., Kubatka, P., Liskova, A., & Büsselberg, D. (2018). Flavonoids in cancer and apoptosis. *Cancers*, *11*(1), 28.

[29] Benavente-Garcia, O., & Castillo, J. (2008). Update on uses and properties of citrus flavonoids: new findings in anticancer, cardiovascular, and anti-inflammatory activity. *Journal of agricultural and food chemistry*, *56*(15), 6185-6205.

[30] Singh, M., Kaur, M., & Silakari, O. (2014). Flavones: An important scaffold for medicinal chemistry. *European journal of medicinal chemistry*, *84*, 206-239.

[31] Dixon, R. A., Xie, D. Y., & Sharma, S. B. (2005). Proanthocyanidins–a final frontier in flavonoid research?. *New phytologist*, *165*(1), 9-28.

[32] Haslam, E. (1989). Plant Polyphenols: Vegetable Tannins Revisited. Cambridge University Press.

[33] Hodek, P., Trefil, P., & Stiborová, M. (2002). Flavonoids-potent and versatile biologically active compounds interacting with cytochromes P450. *Chemico-biological interactions*, *139*(1), 1-21.

[34] Babu, S. S., Praveen, V. K., & Ajayaghosh, A. (2014). Functional π-gelators and their applications. *Chemical reviews*, *114*(4), 1973-2129.

[35] Singh, S., Aggarwal, A., Bhupathiraju, N. D. K., Arianna, G., Tiwari, K., & Drain, C. M. (2015). Glycosylated porphyrins, phthalocyanines, and other porphyrinoids for diagnostics and therapeutics. *Chemical reviews*, *115*(18), 10261-10306.

[36] McNamara, D. P., Childs, S. L., Giordano, J., Iarriccio, A., Cassidy, J., Shet, M. S., ... & Park, A. (2006). Use of a glutaric acid cocrystal to improve oral bioavailability of a low solubility API. *Pharmaceutical research*, *23*, 1888-1897.

[37] Jansook, P., Ogawa, N., & Loftsson, T. (2018). Cyclodextrins: structure, physicochemical properties and pharmaceutical applications. *International journal of pharmaceutics*, *535*(1-2), 272-284.

[38] Tsao, R. (2010). Chemistry and biochemistry of dietary polyphenols. *Nutrients*, *2*(12), 1231-1246.

[39] D Archivio, M., Filesi, C., Di Benedetto, R., Gargiulo, R., Giovannini, C., & Masella, R. (2007). Polyphenols, dietary sources and bioavailability. *Annali-Istituto Superiore di Sanita*, *43*(4), 348.

[40] Dillard, C. J., & German, J. B. (2000). Phytochemicals: nutraceuticals and human health. *Journal of the Science of Food and Agriculture*, *80*(12), 1744-1756.

[41] Ramirez-Estrada, K., Vidal-Limon, H., Hidalgo, D., Moyano, E., Golenioswki, M., Cusidó, R. M., & Palazon, J. (2016). Elicitation, an effective strategy for the biotechnological production of bioactive high-added value compounds in plant cell factories. *Molecules*, *21*(2), 182.

[42] Arulselvan, P., Fard, M. T., Tan, W. S., Gothai, S., Fakurazi, S., Norhaizan, M. E., & Kumar, S. S. (2016). Role of antioxidants and natural products in inflammation. Oxidative medicine and cellular longevity, 2016(1), 5276130.

[43] Perona, J. S., Cabello-Moruno, R., & Ruiz-Gutierrez, V. (2006). The role of virgin olive oil components in the modulation of endothelial function. *The Journal of nutritional biochemistry*, *17*(7), 429-445.

[44] Vermerris, W., & Nicholson, R. (2007). *Phenolic compound biochemistry*. Springer Science & Business Media.

[45] Cushnie, T. T., & Lamb, A. J. (2005). Antimicrobial activity of flavonoids. *International journal of antimicrobial agents*, *26*(5), 343-356.

[46] Vermerris, W., & Nicholson, R. (2007). *Phenolic compound biochemistry*. Springer Science & Business Media.

[47] Brodowska, K. M. (2017). Natural flavonoids: classification, potential role, and application of flavonoid analogues. *European Journal of Biological Research*, *7*(2), 108-123.

[48] Dey, P., Kundu, A., Kumar, A., Gupta, M., Lee, B. M., Bhakta, T., ... & Kim, H. S. (2020). Analysis of alkaloids (indole alkaloids, isoquinoline alkaloids, tropane alkaloids). In *Recent advances in natural products analysis* (pp. 505-567). Elsevier.

[49] Debnath, B., Singh, W. S., Das, M., Goswami, S., Singh, M. K., Maiti, D., & Manna, K. (2018). Role of plant alkaloids on human health: A review of biological activities. *Materials today chemistry*, *9*, 56-72.

[50] Grandclément, C., Tannières, M., Moréra, S., Dessaux, Y., & Faure, D. (2016). Quorum quenching: role in nature and applied developments. *FEMS microbiology reviews*, *40*(1), 86-116.

[51] Dey, P., Kundu, A., Kumar, A., Gupta, M., Lee, B. M., Bhakta, T., ... & Kim, H. S. (2020). Analysis of alkaloids (indole alkaloids, isoquinoline alkaloids, tropane alkaloids). In *Recent advances in natural products analysis* (pp. 505-567). Elsevier.

[52] Rohmer, M. (1999). The discovery of a mevalonate-independent pathway for isoprenoid biosynthesis in bacteria, algae and higher plants. *Natural product reports*, *16*(5), 565-574.

[53] Croteau, R., Kutchan, T. M., & Lewis, N. G. (2000). Natural products (secondary metabolites). *Biochemistry and molecular biology of plants*, *24*, 1250-1319.

[54] Florkin, M. (2014). Unity and diversity in biochemistry: An introduction to chemical biology. Elsevier.

[55] Crellin, J. K., Philpott, J., & Bass, A. T. (1990). Herbal medicine past and present (Vol. 2). Duke University Press.

[56] Cushnie, T. T., Cushnie, B., & Lamb, A. J. (2014). Alkaloids: An overview of their antibacterial, antibiotic-enhancing and antivirulence activities. *International journal of antimicrobial agents*, *44*(5), 377-386.

[57] Othman, L., Sleiman, A., & Abdel-Massih, R. M. (2019). Antimicrobial activity of polyphenols and alkaloids in middle eastern plants. *Frontiers in microbiology*, *10*, 911.

[58] Harris, S. G., Padilla, J., Koumas, L., Ray, D., & Phipps, R. P. (2002). Prostaglandins as modulators of immunity. *Trends in immunology*, *23*(3), 144-150.

[59] Ricciotti, E., & FitzGerald, G. A. (2011). Prostaglandins and inflammation. *Arteriosclerosis, thrombosis, and vascular biology*, *31*(5), 986-1000.

[60] Toure, B. B., & Hall, D. G. (2009). Natural product synthesis using multicomponent reaction strategies. *Chemical reviews*, *109*(9), 4439-4486.

[61] Koehn, F. E., & Carter, G. T. (2005). The evolving role of natural products in drug discovery. *Nature reviews Drug discovery*, *4*(3), 206-220.

[62] Peddibhotla, S. (2009). 3-Substituted-3-hydroxy-2-oxindole, an emerging new scaffold for drug discovery with potential anti-cancer and other biological activities. *Current Bioactive Compounds*, *5*(1), 20-38.

[63] Fuchs, G., Boll, M., & Heider, J. (2011). Microbial degradation of aromatic compounds—from one strategy to four. *Nature Reviews Microbiology*, *9*(11), 803-816.

[64] Harvey, R. G. (1991). Polycyclic aromatic hydrocarbons: chemistry and carcinogenicity. CUP Archive.

[65] Kahkeshani, N., Farzaei, F., Fotouhi, M., Alavi, S. S., Bahramsoltani, R., Naseri, R., ... & Bishayee, A. (2019). Pharmacological effects of gallic acid in health and diseases: A mechanistic review. *Iranian journal of basic medical sciences*, *22*(3), 225.

[66] Mattila, P., & Kumpulainen, J. (2002). Determination of free and total phenolic acids in plant-derived foods by HPLC with diode-array detection. *Journal of agricultural and food chemistry*, *50*(13), 3660-3667.

[67] Herms, D. A., & Mattson, W. J. (1992). The dilemma of plants: to grow or defend. *The quarterly review of biology*, *67*(3), 283-335.

[68] Quideau, S., Deffieux, D., Douat-Casassus, C., & Pouységu, L. (2011). Plant polyphenols: chemical properties, biological activities, and synthesis. *Angewandte Chemie International Edition*, *50*(3), 586-621.

[69] Gill, S. S., & Tuteja, N. (2010). Reactive oxygen species and antioxidant machinery in abiotic stress tolerance in crop plants. *Plant physiology and biochemistry*, *48*(12), 909-930.

[70] Sharma, P., Jha, A. B., Dubey, R. S., & Pessarakli, M. (2012). Reactive oxygen species, oxidative damage, and antioxidative defense mechanism in plants under stressful conditions. *Journal of botany*, *2012*(1), 217037.

[71] Bravo, L. (1998). Polyphenols: chemistry, dietary sources, metabolism, and nutritional significance. *Nutrition reviews*, *56*(11), 317-333.

[72] Singleton, V. L., Orthofer, R., & Lamuela-Raventós, R. M. (1999). [14] Analysis of total phenols and other oxidation substrates and antioxidants by means of folin-ciocalteu reagent. In *Methods in enzymology* (Vol. 299, pp. 152-178). Academic press.

[73] Quideau, S., Deffieux, D., Douat-Casassus, C., & Pouységu, L. (2011). Plant polyphenols: chemical properties, biological activities, and synthesis. *Angewandte Chemie International Edition*, *50*(3), 586-621.

[74] Reed, J. D. (1995). Nutritional toxicology of tannins and related polyphenols in forage legumes. *Journal of animal science*, *73*(5), 1516-1528.

[75] Yang, L., Wen, K. S., Ruan, X., Zhao, Y. X., Wei, F., & Wang, Q. (2018). Response of plant secondary metabolites to environmental factors. *Molecules*, *23*(4), 762.

[76] Teixeira, A., Eiras-Dias, J., Castellarin, S. D., & Gerós, H. (2013). Berry phenolics of grapevine under challenging environments. *International journal of molecular sciences*, *14*(9), 18711-18739.

[77] Deng, Y., & Lu, S. (2017). Biosynthesis and regulation of phenylpropanoids in plants. *Critical reviews in plant sciences*, *36*(4), 257-290.

[78] Siqueira, J. O., Nair, M. G., Hammerschmidt, R., Safir, G. R., & Putnam, A. R. (1991). Significance of phenolic compounds in plant-soil-microbial systems. *Critical Reviews in Plant Sciences*, *10*(1), 63-121.

[79] Yang, L., Wen, K. S., Ruan, X., Zhao, Y. X., Wei, F., & Wang, Q. (2018). Response of plant secondary metabolites to environmental factors. *Molecules*, *23*(4), 762.

[80] Sharma, A., Shahzad, B., Rehman, A., Bhardwaj, R., Landi, M., & Zheng, B. (2019). Response of phenylpropanoid pathway and the role of polyphenols in plants under abiotic stress. *Molecules*, *24*(13), 2452.

[81] Chinnusamy, V., & Zhu, J. K. (2009). Epigenetic regulation of stress responses in plants. *Current opinion in plant biology*, *12*(2), 133-139.

[82] Bruce, T. J., Matthes, M. C., Napier, J. A., & Pickett, J. A. (2007). Stressful "memories" of plants: evidence and possible mechanisms. *Plant science*, *173*(6), 603-608.

[83] Dungait, J. A., Hopkins, D. W., Gregory, A. S., & Whitmore, A. P. (2012). Soil organic matter turnover is governed by accessibility not recalcitrance. *Global Change Biology*, *18*(6), 1781-1796.

[84] Dorais, M., Ehret, D. L., & Papadopoulos, A. P. (2008). Tomato (Solanum lycopersicum) health components: from the seed to the consumer. *Phytochemistry Reviews*, *7*, 231-250.

[85] Herms, D. A., & Mattson, W. J. (1992). The dilemma of plants: to grow or defend. *The quarterly review of biology*, *67*(3), 283-335.

[86] Gurib-Fakim, A. (2006). Medicinal plants: traditions of yesterday and drugs of tomorrow. *Molecular aspects of Medicine*, *27*(1), 1-93.

[87] Wathes, D. C., Abayasekara, D. R. E., & Aitken, R. J. (2007). Polyunsaturated fatty acids in male and female reproduction. Biology of reproduction, 77(2), 190-201.

[88] Khoo, H. E., Azlan, A., Tang, S. T., & Lim, S. M. (2017). Anthocyanidins and anthocyanins: Colored pigments as food, pharmaceutical ingredients, and the potential health benefits. *Food & nutrition research*.

[89] Tanaka, Y., Sasaki, N., & Ohmiya, A. (2008). Biosynthesis of plant pigments: anthocyanins, betalains and carotenoids. *The Plant Journal*, *54*(4), 733-749.

[90] Samanta, A., Das, G., & Das, S. K. (2011). Roles of flavonoids in plants. *Carbon*, *100*(6), 12-35.

[91] Yoshida, K., Mori, M., & Kondo, T. (2009). Blue flower color development by anthocyanins: from chemical structure to cell physiology. *Natural product reports*, *26*(7), 884-915.

[92] Beare-Rogers, J. L., Dieffenbacher, A., & Holm, J. V. (2001). Lexicon of lipid nutrition (IUPAC Technical Report). *Pure and applied chemistry*, *73*(4), 685-744.

[93] Heldt, H. W., & Piechulla, B. (2021). *Plant biochemistry*. Academic Press.

[94] Van den Berg, H., Faulks, R., Granado, H. F., Hirschberg, J., Olmedilla, B., Sandmann, G., ... & Stahl, W. (2000). The potential for the improvement of carotenoid levels in foods and the likely systemic effects. *Journal of the Science of Food and Agriculture*, *80*(7), 880-912.

[95] Stahl, W., & Sies, H. (2005). Bioactivity and protective effects of natural carotenoids. *Biochimica et Biophysica Acta (BBA)-Molecular Basis of Disease*, *1740*(2), 101-107.

[96] Dudareva, N., Pichersky, E., & Gershenzon, J. (2004). Biochemistry of plant volatiles. *Plant physiology*, *135*(4), 1893-1902.

[97] Dudareva, N., Negre, F., Nagegowda, D. A., & Orlova, I. (2006). Plant volatiles: recent advances and future perspectives. *Critical reviews in plant sciences*, *25*(5), 417-440.

[98] Gershenzon, J., & Dudareva, N. (2007). The function of terpene natural products in the natural world. *Nature chemical biology*, *3*(7), 408-414.

[99] Dudareva, N., Negre, F., Nagegowda, D. A., & Orlova, I. (2006). Plant volatiles: recent advances and future perspectives. *Critical reviews in plant sciences*, *25*(5), 417-440.

[100] Harborne, J. B. (2014). Introduction to ecological biochemistry. Academic press.

[101] Ignat, I., Volf, I., & Popa, V. I. (2011). A critical review of methods for characterisation of polyphenolic compounds in fruits and vegetables. *Food chemistry*, *126*(4), 1821-1835.

[102] Cheynier, V., Comte, G., Davies, K. M., Lattanzio, V., & Martens, S. (2013). Plant phenolics: recent advances on their biosynthesis, genetics, and ecophysiology. *Plant physiology and biochemistry*, *72*, 1-20.

[103] Chalker-Scott, L. (1999). Environmental significance of anthocyanins in plant stress responses. *Photochemistry and photobiology*, *70*(1), 1-9.

[104] Chapin, F. S., Bloom, A. J., Field, C. B., & Waring, R. H. (1987). Plant responses to multiple environmental factors. Bioscience, 37(1), 49-57.

[105] Yang, L., Wen, K. S., Ruan, X., Zhao, Y. X., Wei, F., & Wang, Q. (2018). Response of plant secondary metabolites to environmental factors. *Molecules*, *23*(4), 762.

[106] Acamovic, T., & Brooker, J. D. (2005). Biochemistry of plant secondary metabolites and their effects in animals. *Proceedings of the Nutrition Society*, *64*(3), 403-412.

[107] Saxena, M., Saxena, J., Nema, R., Singh, D., & Gupta, A. (2013). Phytochemistry of medicinal plants. *Journal of pharmacognosy and phytochemistry*, *1*(6), 168-182.

[108] Bernays, E. A., & Chapman, R. F. (2007). *Host-plant selection by phytophagous insects* (Vol. 2). Springer Science & Business Media.

[109] Wink, M. (2003). Evolution of secondary metabolites from an ecological and molecular phylogenetic perspective. *Phytochemistry*, *64*(1), 3-19.

[110] Babu, S., & Jayaraman, S. (2020). An update on β-sitosterol: A potential herbal nutraceutical for diabetic management. *Biomedicine & Pharmacotherapy*, *131*, 110702.

[111] Saeidnia, S., Manayi, A., Gohari, A. R., & Abdollahi, M. (2014). The story of beta-sitosterol-a review.

[112] Smith, W. K., Vogelmann, T. C., DeLucia, E. H., Bell, D. T., & Shepherd, K. A. (1997). Leaf form and photosynthesis. *BioScience*, *47*(11), 785-793.

[113] Dickison, W. C. (2000). *Integrative plant anatomy*. Elsevier.

[114] Keller, M. (2020). *The science of grapevines*. Academic press.

[115] Isah, T. (2019). Stress and defense responses in plant secondary metabolites production. *Biological research*, *52*.

[116] Heldt, H. W., & Piechulla, B. (2021). *Plant biochemistry*. Academic Press.

[117] Wasternack, C., & Hause, B. (2002). Jasmonates and octadecanoids: signals in plant stress responses and development.

[118] Gan, S. (Ed.). (2007). *Senescence processes in plants* (p. 322). Blackwell Pub..

[119] Cushnie, T. T., Cushnie, B., & Lamb, A. J. (2014). Alkaloids: An overview of their antibacterial, antibiotic-enhancing and antivirulence activities. *International journal of antimicrobial agents*, *44*(5), 377-386.

[120] Croteau, R., Kutchan, T. M., & Lewis, N. G. (2000). Natural products (secondary metabolites). *Biochemistry and molecular biology of plants*, *24*, 1250-1319.

[121] Ksouri, R., Ksouri, W. M., Jallali, I., Debez, A., Magné, C., Hiroko, I., & Abdelly, C. (2012). Medicinal halophytes: potent source of health promoting biomolecules with medical, nutraceutical and food applications. *Critical reviews in biotechnology*, *32*(4), 289-326.

[122] Basu, A., Nguyen, A., Betts, N. M., & Lyons, T. J. (2014). Strawberry as a functional food: an evidence-based review. *Critical reviews in food science and nutrition*, *54*(6), 790-806.

[123] Saleem, M. (2009). Lupeol, a novel anti-inflammatory and anti-cancer dietary triterpene. *Cancer letters*, *285*(2), 109-115.

[124] Laszczyk, M. N. (2009). Pentacyclic triterpenes of the lupane, oleanane and ursane group as tools in cancer therapy. *Planta medica*, *75*(15), 1549-1560.

[125] Vega-Gálvez, A., Miranda, M., Vergara, J., Uribe, E., Puente, L., & Martínez, E. A. (2010). Nutrition facts and functional potential of quinoa (Chenopodium quinoa willd.), an ancient Andean grain: a review. *Journal of the Science of Food and Agriculture*, *90*(15), 2541-2547.

[126] Li, S. Q., & Zhang, Q. H. (2001). Advances in the development of functional foods from buckwheat. *Critical reviews in food science and nutrition*, *41*(6), 451-464.

[127] Blasbalg, T. L., Hibbeln, J. R., Ramsden, C. E., Majchrzak, S. F., & Rawlings, R. R. (2011). Changes in consumption of omega-3 and omega-6 fatty acids in the United States during the 20th century. *The American journal of clinical nutrition*, *93*(5), 950-962.

[128] Innes, J. K., & Calder, P. C. (2018). Omega-6 fatty acids and inflammation. Prostaglandins, Leukotrienes and Essential Fatty Acids, 132, 41-48.

[129] Lapasin, R. (2012). Rheology of industrial polysaccharides: theory and applications. Springer Science & Business Media.

[130] Bouyer, E., Mekhloufi, G., Rosilio, V., Grossiord, J. L., & Agnely, F. (2012). Proteins, polysaccharides, and their complexes used as stabilizers for emulsions: Alternatives to synthetic surfactants in the pharmaceutical field?. *International journal of pharmaceutics*, *436*(1-2), 359-378.

[131] Lawrence, P. K., & Koundal, K. R. (2002). Plant protease inhibitors in control of phytophagous insects. *Electronic Journal of Biotechnology*, *5*(1), 5-6.

[132] Van Der Hoorn, R. A. (2008). Plant proteases: from phenotypes to molecular mechanisms. *Annu. Rev. Plant Biol.*, *59*(1), 191-223.

[133] Meena, K. K., Sorty, A. M., Bitla, U. M., Choudhary, K., Gupta, P., Pareek, A., ... & Minhas, P. S. (2017). Abiotic stress responses and microbe-mediated mitigation in plants: the omics strategies. *Frontiers in plant science*, *8*, 172.

[134] Dubey, A., Malla, M. A., Khan, F., Chowdhary, K., Yadav, S., Kumar, A., ... & Khan, M. L. (2019). Soil microbiome: a key player for conservation of soil health under changing climate. *Biodiversity and Conservation*, *28*, 2405-2429.

[135] Dudareva, N., Klempien, A., Muhlemann, J. K., & Kaplan, I. (2013). Biosynthesis, function and metabolic engineering of plant volatile organic compounds. *New Phytologist*, *198*(1), 16-32.

[136] Facchini, P. J. (2001). Alkaloid biosynthesis in plants: biochemistry, cell biology, molecular regulation, and metabolic engineering applications. *Annual review of plant biology*, *52*(1), 29-66.

[137] Cheesman, M. J., Ilanko, A., Blonk, B., & Cock, I. E. (2017). Developing new antimicrobial therapies: are synergistic combinations of plant extracts/compounds with conventional antibiotics the solution?. *Pharmacognosy reviews*, *11*(22), 57.

[138] Doughari, J. H. (2012). Phytochemicals: extraction methods, basic structures and mode of action as potential chemotherapeutic agents (pp. 1-33). Rijeka, Croatia: INTECH Open Access Publisher.

[139] Hoxhaj, G., & Manning, B. D. (2020). The PI3K–AKT network at the interface of oncogenic signalling and cancer metabolism. *Nature Reviews Cancer*, *20*(2), 74-88.

[140] He, C., & Klionsky, D. J. (2009). Regulation mechanisms and signaling pathways of autophagy. *Annual review of genetics*, *43*(1), 67-93.

[141] Zhu, H., Li, C., & Gao, C. (2020). Applications of CRISPR–Cas in agriculture and plant biotechnology. *Nature Reviews Molecular Cell Biology*, *21*(11), 661-677.

[142] Cheynier, V., Comte, G., Davies, K. M., Lattanzio, V., & Martens, S. (2013). Plant phenolics: recent advances on their biosynthesis, genetics, and ecophysiology. *Plant physiology and biochemistry*, *72*, 1-20.

[143] Aqil, F., Ahmad, I., & Mehmood, Z. (2006). Antioxidant and free radical scavenging properties of twelve traditionally used Indian medicinal plants. *Turkish journal of Biology*, *30*(3), 177-183.

[144] Kim, D. O., Lee, K. W., Lee, H. J., & Lee, C. Y. (2002). Vitamin C equivalent antioxidant capacity (VCEAC) of phenolic phytochemicals. *Journal of Agricultural and food chemistry*, *50*(13), 3713-3717.

[145] Choi, C. W., Kim, S. C., Hwang, S. S., Choi, B. K., Ahn, H. J., Lee, M. Y., ... & Kim, S. K. (2002). Antioxidant activity and free radical scavenging capacity between Korean medicinal plants and flavonoids by assay-guided comparison. *Plant science*, *163*(6), 1161-1168.

[146] Parekh, J., & Chanda, S. (2007). In vitro antimicrobial activity and phytochemical analysis of some Indian medicinal plants. *Turkish journal of biology*, *31*(1), 53-58.

[147] Barbieri, R., Coppo, E., Marchese, A., Daglia, M., Sobarzo-Sánchez, E., Nabavi, S. F., & Nabavi, S. M. (2017). Phytochemicals for human disease: An update on plant-derived compounds antibacterial activity. *Microbiological research*, *196*, 44-68.

[148] Savoia, D. (2012). Plant-derived antimicrobial compounds: alternatives to antibiotics. *Future microbiology*, *7*(8), 979-990.

[149] Talhouk, R. S., Karam, C., Fostok, S., El-Jouni, W., & Barbour, E. K. (2007). Anti-inflammatory bioactivities in plant extracts. *Journal of medicinal food*, *10*(1), 1-10.

[150] Ullah, A., Munir, S., Badshah, S. L., Khan, N., Ghani, L., Poulson, B. G., ... & Jaremko, M. (2020). Important flavonoids and their role as a therapeutic agent. *Molecules*, *25*(22), 5243.

[151] Serhan, C. N., Chiang, N., & Van Dyke, T. E. (2008). Resolving inflammation: dual anti-inflammatory and pro-resolution lipid mediators. *Nature Reviews Immunology*, *8*(5), 349-361.

[152] Wojdasiewicz, P., Poniatowski, Ł. A., & Szukiewicz, D. (2014). The role of inflammatory and anti-inflammatory cytokines in the pathogenesis of osteoarthritis. *Mediators of inflammation*, *2014*(1), 561459.