Jurnal Kultivasi Vol. 24(3) December 2025
ISSN: 1412-4718, eISSN: 2581-138x

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A review of bioactive compounds of *Caesalpinia sappan*: Pre- and post-harvest effect

Abstract. Sappanwood (*Caesalpinia sappan* L.) is a shrub or small tree that thrives in tropical regions and has been widely distributed across various areas. It has long been used as a natural dye in textiles, cosmetics, and herbal beverages due to its content of various bioactive compounds. This literature review discusses the secondary metabolites in sappanwood, their health benefits, and strategies to enhance product quality through pre-harvest and post-harvest treatments. This literature review was conducted by searching for relevant journals on Google Scholar using relevant keywords. Sappanwood contains diverse secondary metabolites, including flavonoids, phenolics, anthraquinones, triterpenoids, steroids, alkaloids, and tannins, with the heartwood generally having the highest concentration, particularly of brazilin. Various production techniques have been studied to optimize morphological and physiological traits as well as secondary metabolite content, such as adjusting planting density and applying different types of fertilizers. Post-harvest treatments, including drying and blanching, are also critical as they influence product quality and bioactive compound retention.

Keywords: Antioxidant · Drying · Fertilizer · Planting density · Secondary metabolites

Submitted: 2 August 2025, Accepted: 25 December 2025, Published: 31 December 2025
DOI: https://doi.org/10.24198/kultivasi.v24i3.65857

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Rachman AL, Rosniawaty S, Mubarok S, Suherman C, Maxiselly Y. 2025. A review of bioactive compounds of *Caesalpinia sappan*: Pre- and post-harvest effect. Jurnal Kultivasi, 24(3): 268-287.

ISSN: 1412-4718, eISSN: 2581-138x

Introduction

Sappanwood (*Caesalpinia sappan* L.) is a shrub or small tree that thrives in tropical regions and has been widely distributed across various regions, including Asia, Africa, America, and Europe (Uddin et al., 2015). This species is commonly found in Southeast Asia (Thanayutsiri et al., 2023) and is native to, as well as still grows wild in, several regions of South and Southeast Asia, such as southern India, West Bengal, Orissa, Madhya Pradesh, the Malay Peninsula, Sri Lanka (Ahmed et al., 2024), and the Pacific Islands (Dapson & Bain, 2015). Sappanwood has been utilized as a medicinal plant in various countries, including India, Sri Lanka, Myanmar, Vietnam, the Malay Peninsula (Ahmed et al., 2024), and Thailand (Srisaikham & Rupitak, 2020). Sappanwood serves as a natural red dye and has been extensively utilized in textile dyeing (Kannathasan & Kokila, 2021), cosmetic formulations (Agustin & Pratiwi, 2023), and herbal beverages, which are traditionally consumed either as a sole ingredient or in combination with other medicinal herbs (Septiyani et al., 2024). In Indonesia, wedang uwuh is a traditional herbal beverage that contains sappanwood as one of its ingredients and has been traditionally consumed (Setyowati et al.,2023).

Indonesians are very interested in traditional medicine. In Indonesia, herbal medicine (jamu) remains an integral part of traditional healthcare practices and is widely available in traditional markets across the country (Mardiyanto et al., 2023). A recent study reported that the prevalence of herbal medicine use reached 68% (431 out of 634 respondents), with 40% (219 out of 549 individuals who reported illness) practicing self-medication using herbal remedies during the past six months (Rahayu et al., 2020). Sappanwood is widely recognized as a promising plant for pharmaceutical development due to its rich content of bioactive compounds and diverse pharmacological activities.

Pharmacological activity is derived from a plant's bioactive compounds, which are typically classified as secondary metabolites. Secondary metabolites are organic molecules derived from primary metabolites through physiological processes in plants (Twaij & Hasan, 2022). Secondary metabolites are produced and regulated through primary metabolic pathways (Caretto et al., 2015), which not only supply the energy essential for plant development but also generate the carbon skeletons required for their biosynthesis (Liu et al., 2017). While primary metabolites—such as carbohydrates, lipids, and proteins—play a direct role in plant growth and development, secondary metabolites primarily function in defense mechanisms and facilitating interactions with the surrounding environment (Jan et al., 2021).

Secondary metabolites in sappanwood can be classified into groups such as flavonoids, phenolics, anthraquinones, triterpenoids, steroids, alkaloids, and tannins (Vij et al., 2023). These secondary metabolites also include antioxidant compounds such as homoiso-flavonoids, notably brazilin and protosappanin, which exhibit strong antioxidant, anti-inflammatory, and anticancer activities (Nirmal et al., 2015). The brazilin compound, which gives the red color to sappanwood, is known to have benefits in pharmacology as an antioxidant, antibacterial, anti-inflammatory, antihyperglycemic, and analgesic properties (Settharaksa et al., 2019).

Sappanwood naturally occurs in regions characterized by clay, limestone, or sandy soils, predominantly at low to moderate altitudes (ICRAF, 2023). However, the lack of proper and sustainable cultivation practices, including adequate nutrient management and controlled agronomic interventions, may lead to a gradual decline in its natural populations within native habitats. On the other hand, sappanwood possesses considerable potential as a source of secondary metabolites, whose biosynthesis and accumulation can be enhanced through specific cultivation strategies, such as phytohormone application and nutrient management. Applying mineral nutrients as supplements can potentially promote plant growth and regulate the accumulation of secondary metabolites (Yang et al., 2018). Most previous review articles have primarily focused on phytochemical composition and pharmacological activities, while discussions on cultivation strategies that regulate secondary metabolite accumulation remain limited. Therefore, this review aims to discuss cultivation strategies that can be applied to sappanwood, particularly phytohormone application, and nutrient supplementation to enhance secondary metabolite production.

ISSN: 1412-4718, eISSN: 2581-138x

Materials and Methods

In conducting this literature review, relevant keywords were first identified in English, which served as the primary search method to locate related journal articles on Google Scholar. Keywords in Indonesian were also used as a supplementary search strategy to ensure broader coverage of locally published studies. The journal search was conducted from May 15, 2024, to December 24, 2025. The keywords used included: "Origin of the sappanwood plant", "benefits of the sappanwood", "sappanwood as a natural dye", "utilization of sappanwood in traditional medicine in Indonesia", "pharmacological activities of sappanwood", "secondary metabolites of sappanwood", "benefits of secondary metabolites in sappanwood", "relationship between secondary metabolites and antioxidant activity", "antioxidant activity of sappanwood", "antioxidant potential of sappanwood", "brazilin and brazilein as the major characteristic compounds of sappanwood", "mechanisms of brazilin and brazilein as antioxidants in sappanwood", "mechanisms of brazilin and brazilein in the human body as therapeutic agents", "seconday metabolites from different parts of sappanwood", "preharvest of sappanwood", "crop pattern of sappanwood","phytohormones in plants", "functions of phytohormones", "utilization of phytohormones as plant growth regulators, "application of phytohormones in various medicinal plants", "application of phytohormones in sappanwood cultivation", "nutrient application as a plant cultivation technique" , "role of mineral nutrients in enhancing secondary metabolites and antioxidant activity", "use of fertilizers to increase antioxidant activity and secondary metabolite production", "fertilizer application and nutrient management in medicinal plants", "fertilizer application to enhance secondary metabolite production in sappanwood", "post harvest technique for sappanwood", "post harvest technique for woody plant", "effect of drying for sappanwood product", and "effect of blanching for sappanwood product". Most of the articles were published within the past decade. This review discusses a total of 111 publications, written mostly in English.

Results and Discussion

Secondary metabolites in *Caesalpinia sappan* L.
The secondary metabolites contained in sappanwood provide numerous medicinal benefits. Multiple studies confirm that sappanwood extracts are rich in polyphenols and flavonoids, which are responsible for their potent antioxidant effects (Artati et al., 2025). Extracts with higher total phenolic (TPC) and total flavonoid content (TFC) consistently show stronger free radical scavenging activity (Masturi et al., 2021). The secondary metabolite content in sappanwood is presented in more detail in Table 1.

Table 1. Secondary metabolites found in sappanwood

Class	Compounds	Medicinal uses	References
Flavonoid	brazilin, hematoxylin, protosappanin, brazilein, 3'-O-metilbrazilin, sappanin, chalcone, and sappancalchone	Antioxidant, anti-inflammatory, anticancer, analgesic	(Niu et al., 2020; Vij et al., 2023)
Phenolic	Chlorogenic acid, caffeic acid, and gallic acid	Antioxidant and anti-inflammatory	(Sakti et al., 2019)
Anthraquinone	Brazilin, brazilein, and sappanone-A	Antimicrobial, anticancer, and anti-inflammatory	(Ahmad et al., 2020b)
Triterpenoid	Lupeol, β-amyrin, and cycloartenol	Antimicrobial, anticancer, and anti-inflammatory	(Rajput et al., 2022)
Steroid	Stigmasterol and β-sitostero	Anticancer and anti-inflammatory	(Tu et al., 2022)
Alkaloid	Sappan chalcone and sappanone B	Anticancer and anti-inflammatory	(Tamburini, 2019)
Tannin	Gallic acid and ellagic acid	Provides astringent taste	(Vij et al., 2023)

Table 2. Secondary metabolite profile of different plant parts of sappanwood

Plant Part	Identified Secondary Metabolites	Key findings	References
Branch (Sapwood & Heartwood)	alkaloids, triterpenoids (except branch sapwood), Tannins, saponin, phenolic	The total phenolic content and antioxidant activity in branch sapwood were higher than those in branch heartwood.	(Arsiningtyas, 2021)
Middle Stem (Sapwood & Heartwood)	Alkaloid, tannins, saponins, triterpenoid, phenolic	The total phenolic content and antioxidant activity in middle stem sapwood were higher than those in middle stem heartwood.	(Arsiningtyas, 2021)
Main Trunk (Sapwood & Heartwood)	alkaloids, triterpenoids, tannins, saponins, phenolic	The total phenolic content in main trunk sapwood was lower than that in main trunk heartwood; however, the antioxidant activity of main trunk sapwood was higher than that of main trunk heartwood.	(Arsiningtyas, 2021)
Bark	Flavonoid, antioxidant activity	Flavonoid total 0.170 ± 0.10 mg QE/100 g extract.	(Nurulita & Harahap, 2025)
Seed	Flavonoid, antioxidant activity	Flavonoid total 0.032 ± 0.12 mg QE/100 g extract.	(Nurulita & Harahap, 2025)
Leaves	Flavonoid, antioxidant activity	Flavonoid total 0.147 ± 0.002 mg QE/100 g extract.	(Nurulita & Harahap, 2025)
Sappanwood product (samples from local markets in Bandung, Indonesia)	Alkaloid, triterpernoid, phenolic, flavonoid	Flavonoids play a major role in the extract's antioxidant activity, contributing to an effectiveness of up to 80%.	(Artati et al., 2025)
Seed	Caesalsappanin R and caesalsappanin S	Two new cassane-type diterpenoids (1(R) and 2(S)) were isolated from Caesalpinia sappan, with compound 1 showing in vitro antiplasmodial activity (IC_{50} = 3.60 μM).	(Zhu et al., 2017)

Brazilin and brazilein represent the key secondary metabolites characteristic of sappanwood. Brazilin is the major flavonoid found in sappanwood and has shown potential for medicinal applications (Septiani et al., 2022). The secondary metabolites in sappanwood are predominantly concentrated in the stem region, including the bark, wood, and heartwood (Vij et al., 2023), with the pith being identified as the primary site of brazilin accumulation (Rosniawaty, et al., 2024b). Figure 1 illustrates the stem region where secondary metabolites are concentrated.

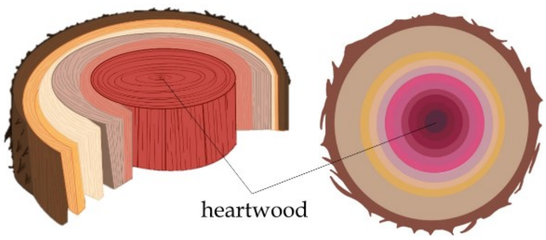

Figure 1. Illustration of the Stem of Sappanwood (*Caesalpinia sappan* L.) Showing the Presence of Secondary Metabolites in the Inner Tissues

Previous studies consistently report that the heartwood is the richest source of bioactive secondary metabolites, particularly phenolic compounds such as brazilin and brazilein, which are responsible for the characteristic red color and strong antioxidant activity of sappanwood. The extraction of sappanwood wood involves felling the trees, irrespective of whether they grow wild in forests or are planted in domestic gardens (Arsiningtyas, 2021). Conservation of sappanwood can be achieved by harvesting wood selectively from branches or the central portions of the tree, rather than felling it entirely (Arsiningtyas, 2021). This practice promotes regrowth and mitigates the risk of extinction. Additionally, the distinction between heartwood and sapwood is important, as these compartments possess different secondary metabolites that may influence their respective antioxidant activities (Miranda et al., 2017). Table 2 shows that different parts of sappanwood contain diverse secondary metabolites with varying concentrations. Table 2 indicates that heartwood tends to produce higher levels of secondary metabolites, particularly phenolic compounds that contribute to the tree's natural durability. The higher yield in heartwood compared to the middle and branch sections is likely due to the increasing extractive content with wood age (de Paula et al., 2019).

Scientific studies have validated many of sappanwood for traditional uses, brazilin and brazilein are proven to reduce inflammation, enhance blood circulation (Mueller et al., 2016), and protect against oxidative stress (Vij et al., 2023), supporting their potential for modern therapeutic applications. Brazilin, in particular, has demonstrated potential in lowering blood glucose, improving glucose metabolism, and even inhibiting the formation of toxic protein fibrils, which may help in treating infections and promoting wound healing (Septiani et al., 2022; Xuan et al., 2022). Brazilein, meanwhile, is noted for its stability as a dye and its medicinal effects, including cytotoxic activity against cancer cells and the ability to suppress melanin synthesis, making it useful in medicine (Ngamwonglumlert et al., 2020).

Brazilin is a yellow-orange crystalline compound found in sappanwood. Brazilin is readily oxidized to brazilein, which produces the vivid red color characteristic of sappanwood extracts, a transformation that is particularly enhanced in alcoholic and aqueous solutions under air exposure or alkaline conditions (Vij et al., 2023). Brazilin and brazilein are two primary bioactive compounds isolated from sappanwood, both of which exhibit a wide range of pharmacological properties with well-studied mechanisms of action. Table 3 shows the mechanism of brazilin and brazilein as a medicinal treat.

Brazilin demonstrates anticancer properties by inducing apoptosis (programmed cell death) through the upregulation of proteins such as Bcl-2, p21, caspase-3/-7, and PARP, and by inhibiting cancer cell growth through ROS-mediated activation of NF-κB (Nava-Tapia et al., 2022; He et al., 2017). Brazilin exerts anti-inflammatory effects by inhibiting NF-κB activation, leading to reduced expression of pro-inflammatory cytokines and suppression of TACE enzyme activity (Tumor Necrosis Factor-α Converting Enzyme) (Amarawati et al., 2019), along with mitigating tissue oxidative stress (He et al., 2017). Brazilin's antioxidant activity is associated with the activation of the SIRT3/GPX4 signaling pathway, which plays a crucial role in protecting cells from oxidative stress and ferroptosis—a type of cell death driven by the accumulation of iron-dependent lipid peroxides (Yan et al., 2025). Brazilin also demonstrates neuroprotective effects by preventing amyloid beta (Aβ) aggregation, a key pathological feature of both Alzheimer's (Cui et al., 2024) and Parkinson's diseases (Nava-Tapia et al., 2022). This mechanism involves hydrophobic interactions and hydrogen bonding with Aβ, facilitating the remodeling of amyloid plaques. Brazilin has also been reported to exhibit antidepressant and anxiolytic effects by mitigating oxidative stress and inflammation in the central nervous system (Jamaddar et al., 2023).

Brazilein, the oxidized derivative of brazilin, also exhibits strong anticancer activity by inducing apoptosis, inhibiting epithelial–mesenchymal transition (EMT), and downregulating PD-L1 expression, a key molecule in cancer immune evasion (Wudtiwai et al., 2023). Brazilein exerts its biological effects through the modulation of several signaling pathways, such as AKT, NF-κB, and GSK3β/β-catenin, and additionally suppresses the activity of matrix metalloproteinases (MMPs), enzymes that contribute to extracellular matrix degradation during the metastatic process (Wudtiwai et al., 2023). Its anti-inflammatory effects are mediated through mechanisms similar to those of brazilin, including TACE inhibition, reduction of pro-inflammatory cytokines, and immunomodulation (Amarawati et al., 2019).

Table 3. Mechanisms of action of brazilin and brazilein as therapeutic agents in humans

Compound	Therapeutic Effects	Main Mechanisms	References
Brazilin	Anticancer (induces apoptosis, inhibits proliferation, autophagy in various cancers)	Induces apoptosis (Bcl-2, p21, caspases, PARP), inhibits proliferation, triggers autophagy via ROS-NF-κB,	(He et al., 2017; Jamaddar et al., 2023; Nava-Tapia et al., 2022; Raptania et al., 2024)
		Blocks JNK, regulates Nrf2, chelates iron.	
	Anti-inflammatory (inhibits NF-κB, NLRP3 inflammasome, reduces cytokines, protects tissues)	Inhibits NF-κB pathway, suppresses pro-inflammatory cytokines, inhibits TACE, reduces oxidative stress	(Amarawati et al., 2019; Jamaddar et al., 2023; Nava-Tapia et al., 2022; Yan et al., 2025)
	Antioxidant (protects against oxidative stress, reduces ferroptosis)	Enhances SIRT3/GPX4 pathway, reduces mitochondrial oxidative stress and ferroptosis	(Jamaddar et al., 2023; Nava-Tapia et al., 2022; Yan et al., 2025)
	Neuroprotective (inhibits amyloid β aggregation, potential for Alzheimer's and Parkinson's disease)	Inhibits Aβ fibrillogenesis, remodels amyloid fibrils, binds Aβ via hydrophobic and hydrogen bonding	(Cui et al., 2024; Nava-Tapia et al., 2022)
	Antidepressant/Anxiolytic (reduces oxidative stress and inflammation in neural tissues)	Inhibits oxidative stress and inflammation in neural tissues	(Jamaddar et al., 2023)
Brazilein	Anticancer (induces apoptosis, inhibits EMT and PD-L1, reduces metastasis in breast cancer)	Induces apoptosis, suppresses EMT and PD-L1 via inhibition of AKT, NF-κB, GSK3β/β-catenin, inhibits MMPs	(Wudtiwai et al., 2023)
	Anti-inflammatory (inhibits TNF-α converting enzyme, potential for rheumatoid arthritis)	Inhibits TACE, reduces pro-inflammatory cytokines, immunomodulation	(Amarawati et al., 2019; Wudtiwai et al., 2023)

The use of chemical-based medicines is generally effective in treating various diseases; however, their application may be associated with serious side effects in certain cases (Kaushik et al., 2021). Consequently, plant-based medicines and herbal remedies are increasingly regarded as healthier, more natural, and safer alternatives due to their origin from natural resources (Wyk & Prinsloo, 2020). In addition to producing essential primary metabolites, plants are capable of synthesizing a wide range of secondary or specialized metabolites that play crucial roles in plant–environment interactions (Pagare et al., 2015). These secondary metabolites are typically produced in low quantities (less than 1% of dry weight), and their accumulation varies depending on the physiological status, developmental stage, and environmental conditions of the plant (Madani et al., 2021). Importantly, secondary metabolites serve as key indicators of the therapeutic quality of medicinal plants and contribute significantly to their pharmacological properties (Pant et al., 2021). Moreover, these compounds function as defense mechanisms against biotic and abiotic stresses while simultaneously possessing substantial therapeutic potential for the treatment of various human diseases (Hilal et al., 2024).

The distribution and sustainability of medicinal plants are strongly influenced by environmental factors such as climate, altitude, and seasonal fluctuations (Kaushik et al., 2021), highlighting the necessity of appropriate agronomic interventions to ensure their continued availability. In this context, the cultivation of sappanwood as a medicinal plant represents a promising strategy to support the growth of plant-based pharmaceutical industries.

Jurnal Kultivasi Vol. 24(3) December 2025
ISSN: 1412-4718, eISSN: 2581-138x

Production techniques involving the application of plant growth regulators (phytohormones) and optimized fertilization practices have the potential to enhance the plant's capacity to synthesize essential secondary metabolites. The characteristic bioactive compounds of sappanwood, including brazilin and brazilein, are responsible for its therapeutic activity and are closely associated with environmental and agronomic factors that regulate their biosynthesis.

Pre-Harvest Effect on Bioactive Compounds. In sappanwood, applying phytohormones holds the potential to boost the production of secondary metabolites. An overview of phytohormone applications is provided in Table 4. The combination of auxins and cytokinins of the induction callus of sappanwood was more effective in inducing callus formation than the use of a single phytohormone (Bukke & Shankar, 2014). Methyl jasmonate and salicylic acid functioned as elicitors that influenced the growth of sappanwood plants (Rosniawaty et al., 2024b). The results indicated that the separate application of methyl jasmonate at 50 µM and salicylic acid at 50 µM was effective in increasing the number of leaves during the 12 and 14 weeks after planting (WAP) (Rosniawaty et al., 2024b). Treatment with 50 µM salicylic acid resulted in the highest dry weight of sappanwood seedlings compared to other treatments. However, these elicitor applications did not significantly affect plant height or stem diameter. Further investigation by Rosniawaty et al. (2025a) on sapanwood leaves remains inconclusive. However, salicylic acid application has shown particular effectiveness in promoting stem diameter growth, whereas methyl jasmonate, especially when applied under close spacing conditions (1 × 1 m), results in the highest accumulation of phenolic and flavonoid compounds (Rosniawaty et al., 2025a). Additional studies are required to assess the levels of secondary metabolites and antioxidant capacity of sappanwood at harvest, considering its significant potential as a medicinal plant with a wide range of pharmacological activities. A potential interaction exists between plant growth regulators and reactive oxygen species (ROS) in sappanwood, given that ROS can act as signaling molecules that enhance antioxidant activity.

Metabolic activities in plants, including photosynthesis and respiration, result in the formation of various compounds, among them reactive oxygen species (ROS), these ROS are persistently generated in mitochondria, chloroplasts, peroxisomes (Torun et al., 2020), plasma membranes, apoplast and the endoplasmic reticulum and cell walls (Mansoor et al., 2022). Excessive levels of ROS can damage cellular components such as DNA, proteins, and lipids; however, plants employ both enzymatic and non-enzymatic systems to neutralize ROS (Dvořák et al., 2021; Janku et al., 2019; Mansoor et al., 2022). Beyond their role as toxic byproducts, ROS also act as key signaling molecules that modulate plant growth, development, and adaptive responses to environmental stresses (Mhamdi & Van Breusegem, 2018; Wang et al., 2024b; Waszczak et al., 2018). ROS play a signaling role in processes such as cell proliferation, differentiation, programmed cell death, and environmental adaptation, while also interacting with phytohormones and other signaling pathways (Mhamdi & Van Breusegem, 2018; Singh et al., 2016b).

The role of phytohormones for plants is as a regulator of plant growth and development, and also plays a role in responding to stress. Phytohormones, synthesized in small quantities within plant tissues, function as critical regulators of diverse biological processes such as embryogenesis, reproductive development, defense mechanisms, and tolerance to environmental stress (Kashchenko et al., 2021). Based on their chemical structure, phytohormones are classified into several groups, such as auxins, cytokinins (CK), ethylene (ET), gibberellins (GA), brassinosteroids (BR), abscisic acid (ABA), strigolactones, and jasmonates (JA)—all of which have the potential to enhance plant defense mechanisms (Wani et al., 2016).

Gibberellin is one of the phytohormones naturally present in plants, but it can also be applied exogenously through the use of plant growth regulators (PGRs). The application of gibberellin in the form of GA_3 at a concentration of 2 mg/L on *Stevia rebaudiana* resulted in the most effective treatment for enhancing secondary metabolite parameters, such as total phenolic content (TPC: 9.84 mg GAE/g dry weight), total phenolic production (TPP: 147.6 mg/L), total flavonoid content (TFC: 5.12 mg QE/g dry weight), and total flavonoid production (TFP: 76.91 mg/L). This treatment also improved antioxidant activity, reaching 77.2% (Ahmad et al., 2020a). In the medicinal plant *Tinospora* *cordifolia*, gibberellic acid (GA) treatment resulted in a marked increase in total alkaloid content, reaching 9,454 mg/g dry weight (DW) in cell extracts, thereby demonstrating GA's stimulatory effect on alkaloid biosynthesis, the total phenolic content peaked at 3 mg/L GA, with 20,5 mg/g DW in cell extracts, confirming GA's regulatory role in phenolic metabolic pathways (Patel et al, 2024). The increasing concentrations of GA_3 significantly enhance total flavonoid content. GA_3 plays a role in facilitating the formation of secondary metabolites, particularly in flavonoid production (Ahmadi et al., 2020). In ramie (*Boehmeria nivea* L.), exogenous application of gibberellin significantly reduces lignin content in the leaves but not in the stems, and overall, gibberellin treatment effectively decreases lignin accumulation while enhancing flavonoid and chlorogenic acid contents in the forage (Jie et al., 2023). In plantation crops such as tea (*Camellia sinensis*), gibberellin is also known to suppress dormant buds, thereby improving tea quality, including increasing catechin content as an antioxidant (Anjarsari, 2023).

In general, phytohormones function as natural signaling compounds in plants to regulate growth and development, while the application of elicitors as exogenous compounds aims to trigger defense reactions in plants. Various types of elicitors have been investigated for their effects on enhancing the secondary metabolite content in plants. Elicitation is a production technique used to stimulate the production of secondary metabolites in plants. When plants are treated with elicitors (inducing compounds), signaling molecules from the elicitor bind to receptors in the plant under in vitro conditions (Kumari et al., 2020). Elicitors play several aspects, such as : 1) elicitors are considered ecologically safe because they involve activating the innate (endemic) immune potential of plants through gene expression; 2) elicitors provide protective effects against pathogens; 3) when elicitors induce resistance in plants, they activate multiple defense systems rather than relying on a single mechanism; and; 4) elicitors can trigger a broad-spectrum resistance response, protecting plant against various types of pathogens, including fungi, bacteria, and viruses (Kumari et al., 2020). This resistance is considered non-specific because it is not targeted to a particular pathogen but instead enhances the overall plant defense mechanisms.

Based on their source, elicitors are categorized as either abiotic or biotic. Abiotic elicitors are non-living chemical or physical agents such as metal ions including oxalate, cadmium, calcium, europium, and lanthanum (Kumari et al., 2020; Naik & Al-Khayri, 2016).Biotic elicitors are compounds derived from living organisms, including polysaccharides (such as alginate, pectin, chitosan), oligosaccharides (such as guluronate, mannan, galacturonide), peptides (including glutathione), and various molecules derived from bacteria, fungi, algae, and yeast (Bhaskar et al., 2022; Jain et al., 2024; Naik & Al-Khayri, 2016). By activating plant defense responses, elicitors stimulate gene expression and metabolic pathways involved in the production of secondary metabolites such as alkaloids, flavonoids, phenolics, and terpenoids. (Bhaskar et al., 2022).

Phytohormones such as brassinosteroids, jasmonic acid, salicylic acid, strigolactones, and peptide hormones play vital roles in both plant development and stress response regulation (Zhao et al., 2021). Various production techniques involving abiotic and biotic stress treatments have the potential to enhance antioxidant levels in sappanwood. In general, when plants are exposed to stress, genes associated with antioxidant defense are activated, leading to enhanced activity of antioxidant systems to neutralize ROS, which simultaneously accumulate at elevated levels (Sanam et al., 2020). These responses collectively enhance the plant's resilience under stress conditions.

Abiotic stress triggers phytohormone-mediated signaling pathways in plants, leading to the activation of MYB genes, which in turn upregulate antioxidant-related genes and help mitigate stress-induced damage (Zhao et al., 2021). Under high-temperature stress, WRKY genes act as essential components of the jasmonic acid signaling pathway, while ethylene plays a pivotal role in mediating the plant's response to waterlogging stress. Ethylene biosynthesis involves two major enzymes—ACC synthase (ACS) and ACC oxidase (ACO)—both of which are critically involved in the plant's adaptive response to waterlogging conditions. Ethylene signaling is known to modulate physiological responses, including changes in phenolic compounds in tea leaves (Ahammed & Li, 2022). Additionally, antioxidant enzyme activities exhibited differential responses following ACC treatment: the activities of superoxide dismutase

(SOD), peroxidase (POD), and catalase (CAT) decreased, while the activity of ascorbate peroxidase (APX) increased (Ke et al., 2018).

As a phytohormone, salicylic acid (SA) participates in multiple physiological functions and serves as a key signal in stimulating the biosynthesis of secondary metabolites (Gorni et al., 2020). Salicylic acid has synergistic and antagonistic effects with various other plant phytohormones in responding to environmental stress (Wang et al., 2020a). Jasmonic acid and salicylic acid often act synergistically or through overlapping pathways in plant defense mechanisms. Salicylic acid contributes significantly to plant immunity by promoting resistance to diverse pathogens such as fungi, viruses, and bacteria (Singh et al., 2017a), Jasmonic acid (JA), on the other hand, modulates signaling pathways involved in the biosynthesis of compounds essential for plant responses to both biotic and abiotic stresses (Kumari et al., 2020).

Nutrients are an important factor in plant cultivation to achieve optimal quantity and quality of yields. Plants require a balanced supply of nutrients, including both macro- and micronutrients, to support their growth and productivity. Fertilizers provide key nutrients as a vital for plant growth and metabolic function. As key macronutrients, nitrogen (N) and phosphorus (P) significantly contribute to the regulation and enhancement of antioxidant defenses in plants. Mineral nutrients, including C, N, P, K, S, and various micronutrients, function not only as essential resources for plant growth but also as signaling molecules and metabolic substrates that reshape primary metabolic pathways and, consequently, regulate the biosynthesis of phenolics, flavonoids, terpenes, alkaloids, saponins, and other secondary metabolites in plants and microorganisms (Bhat et al., 2020). In plants, nutrient limitation or imbalance redirects metabolic resources from growth toward defense- and quality-related secondary metabolites, increasing secondary metabolites, whereas optimal or high nutrient supply generally favors biomass accumulation at the expense of some carbon-based defenses, although it may enhance nitrogen-containing metabolites or specific essential oils depending on the species and biosynthetic pathway (El-Nakhel et al., 2019). Research shows that the combined application of N and P can significantly increase the activities of key antioxidant enzymes such CAT, peroxidase (PX), SOD, and APX, which help neutralize reactive oxygen species and protect plants from oxidative stress, especially under stress conditions (Jia et al., 2025; Ma et al., 2024; Zhang et al., 2024). Balanced N and P fertilization enhances plant growth and nutrient uptake while simultaneously strengthening antioxidant defenses, leading to improved health, productivity, and resilience across various plant species and environments (Jia et al., 2025; Ma et al., 2024).

The balance of nitrogen plays a crucial role in determining the accumulation of secondary metabolites in medicinal plants. In basil, prolonged low mineral nutrition, with variations in nitrogen level and form, enhanced phenylalanine ammonia-lyase (PAL) activity, increased total phenolic and flavonoid contents, and improved antioxidant capacity, showing strong specificity depending on cultivar and nitrogen form, while roots under nutrient limitation accumulated particularly high levels of caffeic and rosmarinic acids (Jakovljević et al., 2019). In *Lonicera japonica*, nitrate nutrition promotes phenolic metabolite accumulation via enhanced photosynthesis, carbon flux, and phenylpropanoid enzyme activity, while ammonium nutrition shifts metabolism toward amino acids and lignin-related compounds (Cao et al., 2025). In *Panax notoginseng*, nitrogen deficiency increased the C/N ratio, amino acids, and sugars while upregulating genes in the mevalonate (MVA) and methylerythritol phosphate (MEP) pathways, leading to higher total triterpenoid saponins despite decreases in some flavonoids, whereas in ginseng, moderate nitrogen optimized root yield and total ginsenosides and modulated root-associated microbes and soil metabolites, including plant secondary metabolite pathways (Cun et al., 2024; Li et al., 2025).

The use of organic fertilizers, such as compost or biofertilizers, is believed to increase antioxidant activity in sappanwood plants. The nutrient content in organic fertilizers varies depending on their source materials, and easily decomposed materials tend to become more effective sources of nutrients (Purba et al., 2021). Raw rice husk decomposition enriches the soil with N, P, and Potassium (K), contributing to improved nutrient status and fertility (Thiyageshwari et al., 2018). The application of rice husk improves soil physical properties, increases organic matter content, and enhances nutrient availability, which collectively contributes to enhanced root growth, greater biomass accumulation, and elevated chlorophyll levels in sunflower plants (Bashir et al., 2021; Rupngam et al., 2025). Additionally, rice husk amendments can help sunflowers cope with environmental stresses, such as heavy metal contamination, by reducing oxidative stress and increasing the uptake of essential nutrients like N, P, and K (Bashir et al., 2021). Production of *Brassica rupestris* in nitrogen-rich soil resulted in the enhanced accumulation of key bioactive constituents, including total antioxidants, chlorophyll, carotenoids, and vitamin C (ascorbic acid) (Muscolo et al., 2019).

Vermicompost application under drought stress significantly improved the antioxidant profile and yield components of *Thymus vulgaris* by increasing chlorophyll content, carotenoids, essential oils, nutrient absorption (N, P, K), and relative water content (Rahimi et al., 2023). Light water stress increased the amount of oil and oil yield of thyme, with the highest values of 2.61% and 3.68 g/m², respectively (Rahimi et al., 2023). Water stress enhances antioxidant activity by activating enzymes such as SOD, APX, and CAT, which play a role in protecting plants against lipid peroxidation (as indicated by malondialdehyde, MDA, and content). Organic fertilizer application appears to improve antioxidant capacity and thyme yield by increasing water-use efficiency under drought conditions.

The application of chicken, cow, and goat manure had no significant effect on the growth performance of sappanwood plants (Rosniawaty, et al., 2024c). In general, solid or liquid animal manure contains approximately 0.5% N, 0.25% P, and 0.5% K, which serve as essential nutrient sources for plant growth (Purba et al., 2021). The application of cattle manure had no significant effect on branch and leaf growth in purslane (*Portulaca grandiflora*). However, the highest levels of total phenolics (0.1532 mg GAE/g), flavonoids (0.1529 mg GAE/g), and antioxidant activity (0.6440 µmol TE/g fresh) were observed in plants treated with 10 g of cattle manure per polybag (Liwanda et al., 2023).

Applications of organic fertilizers as nutrient supplements in sappanwood production are summarized in Table 4. The use of rice husk as a growing medium of sappanwood showed the greatest stem diameter and the highest total flavonoid content, it increased stem diameter by 45.93% and total flavonoid content by 20.12% compared to the control (Srisaikham & Rupitak, 2020). The use of compost-based growing media can influence both the growth and the content of bioactive compounds in sappanwood (Srisaikham & Rupitak, 2020). The combined application of compost and NPK fertilizer (N:P: K = 21:17:17) at a 1:1 ratio significantly improved the biochemical attributes and antioxidant activity of *Moringa oleifera*, as evidenced by increased carbohydrate levels, phenolic content, and flavonoid accumulation, compared to the sole application of either compost or NPK fertilizer alone (Sarwar et al., 2020).

Although plants produce a wide variety of secondary metabolites, not all of these compounds necessarily confer health benefits to humans. Many secondary metabolites function primarily in plant defense, pigmentation, or stress responses, and their effects on human physiology can vary depending on chemical structure, dosage, and bioavailability. Some secondary metabolites, such as certain flavonoids, phenolics, and saponins, have been reported to exhibit antioxidant properties, which allow them to scavenge ROS and potentially contribute to human health. However, the antioxidant activity of plant secondary metabolites cannot be assumed for all compounds. Further research is therefore needed to identify which secondary metabolites exert health benefits through ROS modulation, similar to the mechanism of conventional antioxidants. Such studies are essential to clarify the specific compounds and mechanisms responsible for the beneficial effects of secondary metabolites in humans.

Jurnal Kultivasi Vol. 24(3) December 2025
ISSN: 1412-4718, eISSN: 2581-138x

Table 4. Pre-harvest conditions of sappanwood

No	Plant Material	Treatment	Experimental conditions	Effect for Sappanwood	References
1	Sappanwood seeds	Indole-3-acetic acid (IAA), α-naphthalene acetic acid (NAA), 6-benzylaminopurine (BAP)	The use of topsoil and cow manure as a growing medium.	Soaking in NAA (1.25 ppm) and BAP (1.25 ppm) produced the best results for leaf number and stem growth of sappanwood seedlings.	Al-Adawiah et al. 2023
2.	Sappanwood seeds	IAA, NAA, BAP	The addition of cow manure (2:1) to the sappanwood growing medium.	Auxin and cytokinin affected the seedling height, stem diameter, number of leaves, leaf area, root length, root dry weight, and stem dry weight of sappanwood seedlings.	Rosniawaty et al., 2023d
3.	Callus of sappanwood	Auxins + cytokinins	The cultures maintained at a temperature of 28±2 °C. at a16-hours light/8-hours dark cycle	Inducing callus formation than the use of a single phytohormone	Bukke & Shankar, 2014
4	Sappanwood seedlings	Cytokinins and giberelins	Foliar spray on sappanwood seedlings	The application of BAP at 60 ppm and gibberellin at 150 ppm produced the highest root length response.	Rosniawaty et al., 2023e
5.	Sappanwood seedlings	Methyl jasmonate at 50 μM and salicylic acid at 50 μM	Foliar spray at two-week intervals	The separate application of phytohormone was effective in increasing the number of leaves during the 12 and 14 weeks after planting (WAP)	Rosniawaty, et al., 2024b
6.	Fresh foliage sample from 16-month-old plants	Salisilyc acid 200 ppm and methyl jasmonate 300 ppm	Foliar spray; spacing 1×1 m, 2×2 m, 3×3 m	Salicylic acid increase stem diaeter, and interactions of 1 x 1 m planting distance with methyl jasmonates improved phenolic and flavonoid total in sappanwood	Rosniawaty et al., 2025a
7.	12 months sappanwood seedlings	Application of chicken, cow, and goat manure	Planting distance levels 1 x 1 m, 2 x 2 m, 3 x 3 m.	An interaction between planting distance and manure application influenced stem diameter of sappanwood at 3 months after planting, manure application showed no significant effect on the measured parameters.	Rosniawaty, et al., 2024c
8.	Fresh foliage samples from 3.5 years old sappanwood plants	Rice husk, coconut coir dust	Different growing media	Rice husk–based growing media produced the greatest stem diameter and highest total flavonoid content in sappanwood compared to the control Similarly, compost-based growing media were shown to influence both plant growth and bioactive compound.	Srisaikham & Rupitak, 2020

Post-Harvest Effect on Bioactive Compound. Post-harvest handling is critical for preserving the quality and bioactive compounds of sappanwood, particularly brazilin, the major phenolic pigment responsible for its red color and antioxidant activity. Improper handling can lead to degradation of bioactive compounds, color loss, and reduced pharmacological efficacy. High drying or storage temperatures accelerate oxidation and hydrolysis of vitamin C, phenols, flavonoids, glycosides, and pigments, reducing antioxidant activity and therapeutic potential (ElGamal et al., 2023). Exposure to air and light promotes oxidation of polyphenols, carotenoids, and anthocyanins, driving color fading and loss of radical-scavenging capacity (Ndhlala et al., 2025). Insufficient drying or storage in a humid environment can promote the growth of mold and microorganisms, which may change the plant's chemical composition and reduce product safety (Patil et al., 2024).

In plants with wood as the target organ, such as cinnamon, wood sorting can determine quality classes based on color, flavor, moisture content, ash content, and oil yield (Izhar & Jendri, 2022). Drying is necessary to prevent mold and to ensure the product can be stored safely for a long period (Baiqi et al., 2019). Drying can be carried out using traditional methods by sun-drying or using controlled heat dryers such as ovens (Baiqi et al., 2019). Post-harvest handling of sappanwood can be seen in Table 5.

Table 5. Post harvest technique of sappanwood

Post-harvest	Purpose	Methods	Key findings	References
Drying	To evaluate the effects of foaming agents and drying temperature on the drying kinetics and phytochemical properties of sappanwood extract powder	The use of foaming agents (egg albumin and gum Arabic) and drying temperatures (40, 60, and 80 °C).	Optimal drying of sappanwood extract was achieved using 5% egg albumin and 25% gum Arabic at 64.1 °C for 64.7 minutes, resulting in a drying process approximately seven times faster than without a foaming agent, while retaining 87.25% of total phenolic compounds.	Utari et al., 2023
Blanching & drying	To identify the optimal method to preserve brazilin, the phytochemical responsible for the red coloration, in a stable and effective form	Steam blanching, water blanching, sun drying, and cabinet drying were evaluated, and the traditional method without blanching and with sun drying was used as the control.	The combination of water blanching and cabinet drying (BCD) produced the highest red color intensity, representing a 48% increase compared to the control. This increase in color intensity was consistent with the higher brazilin content, which was 376% greater than that of the control. In addition, the BCD treatment exhibited the highest antioxidant activity and total phenolic content, with an IC_{50} value of 98.99 ppm and a total phenolic content of 213.12 mg GAE/g. These results indicate that brazilin plays an important role as an antioxidant compound.	Septiyani et al., 2024

ISSN: 1412-4718, eISSN: 2581-138x

Table 5 shows that the drying process affects the secondary metabolite content of sappanwood. Brazilin is highly susceptible to oxidation when exposed to air, heat, light, or pH changes, converting its hydroxyl groups (-OH) into carboxyl groups (-COOH) (Utari et al., 2023). The stability of brazilin also can be influenced by metal ion interactions (Ngamwonglumlert et al., 2020) and temperature of processing the product (Septiyani et al., 2024). Sappanwood is widely used in beverages without pre-treatment, though pH, temperature, and light can significantly affect drink quality and brazilin stability during storage (Putri et al., 2024).

Foam mat drying is applied to stabilize such unstable compounds through the addition of foaming agents. The foam, a gas dispersion in a liquid or solid, is stabilized by surfactants or surface-active agents (Utari et al., 2023; Hardy & Jideani, 2017). Egg albumin, as a foaming agent, enhances lamellar interfacial viscoelasticity and generates small initial bubbles, resulting in a more stable foam (Utari et al., 2023). In contrast, the role of gum Arabic is to form a highly viscous solution due to its large polysaccharide structures, which hinders foam formation and leads to uneven pore distribution in the dried extract (Utari et al., 2023).

Blanching can inactivate enzymes, which may cause undesirable color changes in dried products, while also helping to stabilize bioactive compounds; however, phenolic losses may still occur due to thermal degradation or leaching, reducing antioxidant activity (Deylami et al, 2016). During drying, prolonged heat can degrade pigments and diminish color intensity, and oxidation reactions can further contribute to color changes (ElGamal et al., 2023). In addition, drying affects antioxidant activity through the loss of water-soluble antioxidants, the retention of lipid-soluble compounds, and the Maillard reaction, which is a heat-induced reaction between amino acids and reducing sugars that can lead to browning and alter bioactive compounds (Calín-Sánchez et al., 2020).

Optimized post-harvest strategies—including blanching, controlled drying, and careful extract processing—are essential to maintain the quality, stability, and functional properties of sappanwood. Proper handling not only enhances its pharmacological potential but also supports its use as a standardized raw material for medicinal, functional food, and natural colorant applications.

Conclusion

Sappanwood contains a wide range of secondary metabolites, including flavonoids, phenolics, anthraquinones, triterpenoids, steroids, alkaloids, and tannins, which are suggested to have significant health benefits. These metabolites are distributed in various parts of the plant, with the heartwood generally containing the highest concentration, particularly of brazilin. Numerous production techniques have been studied to optimize morphological and physiological traits as well as the secondary metabolite content that governs antioxidant activity. Practices such as adjusting planting density and applying different types of fertilizers have been shown to enhance these parameters. In addition to pre-harvest treatments, post-harvest processes are also critical, as they determine the quality and properties of sappanwood as an herbal drink. Post-harvest methods such as drying and blanching play a key role in preserving brazilin content and ensuring product quality.

References

Agustin E, Pratiwi A. 2023. The Utilization of Secang Wood (*Caesalpinia sappan* L.) Extract Nanoemulsion as Natural Pigment in Lip Cream Preparations. Journal of Drug Delivery and Therapeutics, 13(10): 54–58. https://doi.org/10.22270/jddt.v13i10.6242

Ahammed GJ, Li X. 2022. Hormonal regulation of health-promoting compounds in tea (*Camellia sinensis* L.). Plant Physiology and Biochemistry, 185: 390–400. https://doi.org/10.1016/j.plaphy.2022.06.021

Ahmad A, Ali H, Khan H, Begam A., Khan S, Ali SS, Ahmad N, Fazal H, Ali M, Hano C, Ahmad N, Abbasi BH. 2020a. Effect of gibberellic acid on production of biomass, polyphenolics and steviol glycosides in adventitious. Plants, 9: 420–434.

Ahmad I, Arifianti AE, Sakti AS, Saputri FC, Mun'im A. 2020b. simultaneous natural deep eutectic solvent-based compounds of Cinnamon bark and Sappan wood as a Dipeptidyl Pepidase IV inhibitor. Molecules, 25: 1–11.

Ahmadi AM, Wulandari RA, Taryono. 2020. Performance of three clones tea (*Camellia sinensis* L.) seedling on the two different seedling media. Vegetalika, 9(2): 359–372.

Ahmed R, Jeyabalan, G, Jeyabalan JB. 2024. Pharmacognostical Studies on the Leaves of *Caesalpinia sappan* Linn (Fabaceae). International journal of pharmaceutical quality assurance, 15(02): 917–923. https://doi.org/10.25258/ijpqa.15.2.59

Al-Adawiah AR, Rosniawaty S, Anjarsari IRD. 2023. Respons peningkatan perkecambahan benih dan pertumbuhan bibit tanaman secang (*Caesalpinia sappan* L.) terhadap penggunaan zat pengatur tumbuh dan media tanam yang berbeda. Jurnal Agrikultura, 66(1): 66–73.

Amarawati GAK, Susanti NMP, Laksmiani NPL. 2019. Aktivitas anti-rheumatoid arthritis dari brazilin dan brazilein secara in silico. Jurnal Kimia, 13(2): 153-158. https://doi.org/10.24843/jchem.2019.v13.i02.p05

Anjarsari IRD. 2023. Potensi penggunaan zat pengatur tumbuh sitokinin dan giberelin pada budidaya teh (*Camellia sinensis* (L.) O. Kuntze) di Indonesia. Agronomika, 21(1): 20–24.

Arsiningtyas IS. 2021. Antioxidant profile of heartwood and sapwood of *Caesalpinia sappan* L. tree's part grown in Imogiri Nature Preserve, Yogyakarta. IOP Conference Series: Earth and Environmental Science, 810(1). https://doi.org/10.1088/1755-1315/810/1/012040

Artati A, Pratama R, Nurisyah N, Asyikin A, Abdullah T, Daswi DR, Dewi R. 2025. Phytochemical testing, antioxidant activity and determination of specific and non-specific parameters of secang wood extract (*Caesalpinia sappan* L.). Journal of Research in Science Education, 11(2):918–929. https://doi.org/10.29303/jppipa.v11i2.10563

Baiqi AU, Utami PP, Anugrah D, Fauzan AA, Ningsih WS, Rusydi MI. 2019. Improving the quality and quantity of cinnamon drying process using art cave in Lambung Bukit West Sumatra. IOP Conference Series: Materials Science and Engineering, 602(1). https://doi.org/10.1088/1757-899X/602/1/012023

Bashir S, Qayyum MA, Husain A, Bakhsh A, Ahmed N, Hussain MB, Elshikh MS, Alwahibi MS, Almunqedhi BMA, Hussain R, Wang YF, ZhouY, Diao ZH. 2021a. Efficiency of different types of biochars to mitigate Cd stress and growth of sunflower (*Helianthus*; L.) in wastewater irrigated agricultural soil. Saudi Journal of Biological Sciences, 28(4): 2453–2459. https://doi.org/10.1016/j.sjbs.2021.01.045

Bhaskar R, Xavier LSE, Udayakumaran G, Kumar DS, Venkatesh R, & Nagella P. 2022. Biotic elicitors: a boon for the in-vitro production of plant secondary metabolites. Plant Cell, Tissue and Organ Culture, 149(1-2): 7-24. https://doi.org/10.1007/s11240-021-02131-1

Bhat B, Islam S, Ali A, Sheikh B, Tariq L, Islam S, Dar T. 2020. Role of micronutrients in secondary metabolism of plants, 311-329. https://doi.org/10.1007/978-3-030-49856-6_13

Bukke AN, Shankar PC. 2014. Effect of different plant growth regulators on callus induction in *Caesalpinia Sappan* L. a medicinal plant. International Journal of Recent Scientific Research, 5(11): 1991–1994.

Calín-Sánchez Á, Lipan L, Cano-Lamadrid M, Kharaghani A, Masztalerz K, Carbonell-Barrachina AA, Figiel A. 2020. Comparison of traditional and novel drying techniques and its effect on quality of fruits, vegetables and aromatic herbs. In Foods 9(9). MDPI AG. https://doi.org/10.3390/foods9091261

Cao Y, Yang Y, Tan Z, Feng X, Tian Z, Liu T, Pan Y, Wang M, Su X, Liang H, Guo S. 2025. Metabolomics combined with photosynthetic analysis reveals potential mechanisms of phenolic compound accumulation in *Lonicera japonica* induced by nitrate nitrogen supply. International Journal of Molecular Sciences, 26. https://doi.org/10.3390/ijms26094464.

Caretto S, Linsalata V, Colella G, Mita G, Lattanzio V. 2015. Carbon fluxes between primary metabolism and phenolic pathway in plant tissues under stress. International Journal of Molecular Sciences, 16(11): 26378–26394. https://doi.org/10.3390/ijms161125967

Cui Z, Qu L, Zhang Q, Lu F, Liu F. 2024. Brazilin-7-2-butenoate inhibits amyloid β-protein aggregation, alleviates cytotoxicity, and protects Caenorhabditis elegans. International Journal of Biological Macromolecules, 264: 1-11.

https://doi.org/10.1016/j.ijbiomac.2024.130695

Cun Z, Zhang J, Hong J, Yang J, Gao L, Hao B, Chen J. 2024. Integrated metabolome and transcriptome analysis reveals the regulatory mechanism of low nitrogen-driven biosynthesis of saponins and flavonoids in *Panax notoginseng*. Gene. https://doi.org/10.1016/j.gene.2024.148163.

Dapson RW, Bain CL. 2015. Brazilwood, sappanwood, brazilin and the red dye brazilein: From textile dyeing and folk medicine to biological staining and musical instruments. Biotechnic and Histochemistry, 90(6): 401–423. https://doi.org/10.3109/10520295.2015.1021381

de Paula PT, Scatolino MV, de Araújo ACC, de Oliveira AFCF, de Figueiredo ICR, de Assis MR, Trugilho PF. 2019. Assessing proximate composition, extractive concentration, and lignin quality to determine appropriate parameters for selection of superior Eucalyptus Firewood. Bioenergy Research, 12(3): 626–641. https://doi.org/10.1007/s12155-019-10004-x

Deylami MZ, Abdul, Tan CP, Bakar J, Olusegun L. 2016. Effect of blanching on enzyme activity, color changes, anthocyanin stability and extractability of mangosteen pericarp: A kinetic study. Journal of Food Engineering, 178: 12–19. https://doi.org/10.1016/J.JFOODENG.2016.01.001

Dvořák P, Krasylenko Y, Zeiner A, Šamaj J, Takáč T. 2021. Signaling toward reactive oxygen species-scavenging enzymes in plants. In Frontiers in Plant Science, 11: 1-24. https://doi.org/10.3389/fpls.2020.618835

ElGamal R, Song C, Rayan AM, Liu C, Al-Rejaie S, ElMasry G. 2023. Thermal degradation of bioactive compounds during drying process of horticultural and agronomic products: A comprehensive overview. In Agronomy 13(6). MDPI. https://doi.org/10.3390/agronomy13061580

El-Nakhel C, Pannico A, Kyriacou M, Giordano M, De Pascale S, Rouphael Y. 2019. Macronutrient deprivation eustress elicits differential secondary metabolites in red and green-pigmented butterhead lettuce grown in closed soilless system. Journal of the science of food and agriculture. https://doi.org/10.1002/jsfa.9985.

Gorni PH, Pacheco AC, Moro AL, Silva JFA, Moreli RR, de Miranda GR, Pelegrini JM, Spera KD, Bronzel JL. & da Silva RMG. 2020. Salicylic acid foliar application increases biomass, nutrient assimilation, primary metabolites and essential oil content inf *Achillea millefolium* L. Scientia Horticulturae, 270: 1-9. https://doi.org/10.1016/j.scienta.2020.109436

Hardy Z, Jideani VA. 2017. Foam-mat drying technology: A review. Critical Reviews in Food Science and Nutrition, 57(12): 2560–2572. https://doi.org/10.1080/10408398.2015.1020359

He ZJ, Zhu FY, Li SS, Zhong L, Tan HY, Wang K. 2017. Inhibiting ROS-NF-κB-dependent autophagy enhanced brazilin-induced apoptosis in head and neck squamous cell carcinoma. Food and Chemical Toxicology, 101: 55–66. https://doi.org/10.1016/j.fct.2017.01.002

Hilal B, Khan MM, Fariduddin Q. 2024. Recent advancements in deciphering the therapeutic properties of plant secondary metabolites: phenolics, terpenes, and alkaloids. Plant Physiology and Biochemistry, 211. https://doi.org/10.1016/J.PLAPHY.2024.108674

ICRAF.2023. Agroforestry Tree Database: *Caesalpinia sappan*. World Agroforestry Centre. https://apps.worldagroforestry.org

Izhar L, Hendri J. 2022. Postharvest standard practices for improving Cinnamon quality product in Kerinci. IOP Conference Series: Earth and Environmental Science, 1024(1). https://doi.org/10.1088/1755-1315/1024/1/012078

Jain D, Bisht S, Parvez A, Singh K, Bhaskar P, Koubouris G. 2024. Effective biotic elicitors for augmentation of secondary metabolite production in medicinal plants. Agriculture (Switzerland), 14(796): 1-24. Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/agriculture14060796

Jakovljević D, Topuzović M, Stanković M. 2019. Nutrient limitation as a tool for the induction of secondary metabolites with antioxidant activity in basil cultivars. Industrial Crops and Products.

https://doi.org/10.1016/j.indcrop.2019.06.025

Jamaddar S, Sarkar C, Akter S, Mubarak MS, El-Nashar HAS, El-Shazly M, Islam MT. 2023. Brazilin: An updated literature-based review on its promising therapeutic approaches and toxicological studies. In South African Journal of Botany, 158: 118-132. Elsevier B.V. https://doi.org/10.1016/j.sajb.2023.04.053

Jan R, Asaf S, Numan M, Lubna, Kim KM. 2021. Plant secondary metabolite biosynthesis and transcriptional regulation in response to biotic and abiotic stress conditions. Agronomy, 11(5): 1–31. https://doi.org/10.3390/agronomy11050968

Janku M, Luhová, L, Petrivalský M. 2019. On the origin and fate of reactive oxygen species in plant cell compartments. In Antioxidants, 8(14): 1-15. MDPI. https://doi.org/10.3390/antiox8040105

Jia S, Zhao X, Huang J, Yao X, Xie F. 2025. Phosphorus alleviates cadmium damage by reducing cadmium accumulation and enhancing antioxidant enzymes at the vegetative phase in Soybean. Agronomy, 15(637): 1-19. https://doi.org/10.3390/agronomy15030637

Jie H, Zhao L, Ma Y, Rasheed A, Jie Y. 2023. Integrated transcriptome and metabolome analysis reveal that exogenous gibberellin application regulates lignin synthesis in ramie. Agronomy, 13(6). https://doi.org/10.3390/agronomy13061450

Kannathasan K, Kokila P. 2021. Dyeing of cotton fabric by *Caesalpinia sappan* aqueous extract at different temperatures and mordants. Current Botany, 12: 188–191. https://doi.org/10.25081/cb.2021.v12.7277

Kashchenko NI, Olennikov DN, Chirikova NK. 2021. Phytohormones and elicitors enhanced the ecdysteroid and glycosylflavone content and antioxidant activity of *Silene repens*. Applied Sciences (Switzerland), 11:1-14. https://doi.org/10.3390/app112311099

Kaushik B, Sharma J, Yadav K, Kumar P, Shourie A. 2021. Phytochemical properties and pharmacological role of plants: secondary metabolites. Biosciences Biotechnology Research Asia, 18(1): 23–35. https://doi.org/10.13005/bbra/2894

Ke SW, Chen GH, Chen CT, Tzen JTC, Yang CY. 2018. Ethylene signaling modulates contents of catechin and ability of antioxidant in *Camellia sinensis*. Botanical Studies, 59(1). https://doi.org/10.1186/s40529-018-0226-x

Kumari N, Varghese BA, Devi S, Khan MA, Jangra S, Kumar A. 2020. Abiotic elicitation: A tool for producing bioactive compounds. Plant Archives, 20: 2683–2689.

Li K, Wan M, Han M, Yang L. 2025. The response of *Panax ginseng* root microbial communities and metabolites to nitrogen addition. BMC Plant Biology, 25. https://doi.org/10.1186/s12870-025-07031-6.

Liu J, Liu Y, Wang Y, Abozeid A, Zu YG, Tang ZH. 2017. The integration of GC–MS and LC–MS to assay the metabolomics profiling in *Panax ginseng* and *Panax quinquefolius* reveals a tissue- and species-specific connectivity of primary metabolites and ginsenosides accumulation. Journal of Pharmaceutical and Biomedical Analysis, 135: 176–185. https://doi.org/10.1016/j.jpba.2016.12.026

Liwanda N, Nurinayah I, Mubayyinah H, Pratiwi ARR, Wahyuningrum T, Ashari RZ, Aisyah SI, Nurcholis W. 2023. Effect of cow manure fertilizer on growth, polyphenol content, and antioxidant activity of purslane plants. International Journal of Chemical and Biochemical Sciences, 23(1): 43–54.

Ma J, Xin X, Cao Y, Zhao L, Zhang Z, Zhang D, Fu Z, Sun J. 2024. Root growth characteristics and antioxidant system of *Suaeda salsa* in response to the short-term nitrogen and phosphorus addition in the Yellow River Delta. Frontiers in Plant Science, 15:1-11. https://doi.org/10.3389/fpls.2024.1410036

Madani H, Escrich A, Hosseini B, Sanchez-Muñoz R, Khojasteh A, Palazon J. 2021. Biomolecule's effect of polyploidy induction on natural metabolite production in medicinal plants. 11. https://doi.org/10.3390/biom

Mansoor S, Wani OA, Lone JK, Manhas S, Kour N, Alam P, Ahmad A, Ahmad P. 2022. Reactive oxygen species in plants: From source to sink. Antioxidants, 11(2): 1-14. MDPI. https://doi.org/10.3390/antiox11020225

Mardiyanto MB, Foresty RS, Arlysia V, Chorunissa ZFN, NugrohoGD, Yasa A, Naim DM, Setyawan AD. 2023. Plants as herbal medicine at Nguter Traditional Market, Sukoharjo, Central Java, Indonesia.

Asian Journal of Ethnobiology, 6(1):65–74. https://doi.org/10.13057/asianjethnobiol/y060108

Masturi, Alighiri D, Edie SS, Hanisyifa U, Drastisianti A. 2021. Determination of total phenol and flavonoid contents and antioxidant activity from extract fraction of sappan wood (*Caesalpinia sappan* l.) by liquid-liquid extraction and vacuum liquid chromatography. Asian Journal of Chemistry, 33(8):1729–1735. https://doi.org/10.14233/ajchem.2021.23029

Mhamdi A, Van Breusegem F. 2018. Reactive oxygen species in plant development. Development (Cambridge), 145: 1-12. https://doi.org/10.1242/dev.164376

Miranda I, Sousa V, Ferreira J, Pereira H. 2017. Chemical characterization and extractives composition of heartwood and sapwood from *Quercus faginea*. PLoS ONE, 12(6). https://doi.org/10.1371/journal.pone.0179268

Mueller M, Weinmann D, Toegel S, Holzer W, Unger FM, Viernstein H. 2016. Compounds from *Caesalpinia sappan* with anti-inflammatory properties in macrophages and chondrocytes. Food and Function, 7(3):1671–1679. https://doi.org/10.1039/c5fo01256b

Muscolo A, Sidari M, Settineri G, Papalia T, Mallamaci C, Attinà E. 2019. Influence of soil properties on bioactive compounds and antioxidant capacity of *Brassica rupestris* Raf. Journal of Soil Science and Plant Nutrition, 19(4): 808–815. https://doi.org/10.1007/s42729-019-00080-5

Naik PM, Al-Khayri JM. 2016. Abiotic and biotic elicitors–role in secondary metabolites production through in vitro culture of medicinal plants. In Abiotic and Biotic Stress in Plants - Recent Advances and Future Perspectives. InTech, 10: 247-277. https://doi.org/10.5772/61442

Nava-Tapia DA, Cayetano-Salazar L, Herrera-Zúñiga LD, Bello-Martínez J, Mendoza-Catalán MA, Navarro-Tito N. 2022. Brazilin: Biological activities and therapeutic potential in chronic degenerative diseases and cancer. In Pharmacological Research, 175: 1-14. Academic Press. https://doi.org/10.1016/j.phrs.2021.106023

Ndhlala AR, Ngobeni GT, Mulaudzi R, Lebelo SL. 2025. Different temperature storage conditions and packaging types affects colour parameters, amino acid composition, microbial contamination, and key bioactive molecules of *Moringa oleifera* Lam. Powder. Molecules, 30(20). https://doi.org/10.3390/molecules30204048

Ngamwonglumlert L, Devahastin S, Chiewchan N, Raghavan GSV. 2020. Color and molecular structure alterations of brazilein extracted from *Caesalpinia sappan* L. under different pH and heating conditions. Scientific Reports, 10: 1-10. https://doi.org/10.1038/s41598-020-69189-3

Nirmal NP, Rajput MS, Prasad RGSV, Ahmad M. 2015. Brazilin from *Caesalpinia sappan* heartwood and its pharmacological activities: A review. Asian Pacific Journal of Tropical Medicine, 8(6): 421–430. https://doi.org/10.1016/j.apjtm.2015.05.014

Niu Y, Wang S, Li C, Wang J, Liu Z, Kang W. 2020. Effective compounds from *Caesalpinia sappan* L. on the Tyrosinase in vitro and in vivo. Natural Product Communications, 15(4): 1–8. https://doi.org/10.1177/1934578X20920055

Nurulita U, Harahap ZA. 2025. 3rd Lawang Sewu International Symposium on Medical and Health Sciences. 1. Spinger Nature. Available at: https://books.google.co.id/books?hl=id&lr=&id=qo9qEQAAQBAJ&oi=fnd&pg=PA304&dq=sappanwood+seedlings&ots=d6Lg4hUMR5&sig=5w_XHz96DH8yqn42PMKGij1yYME&redir_esc=y#v=onepage&q=sappanwood%20seedlings&f=false

Pagare S, Bhatia M, Tripathi N, Pagare S, Bansal YK. 2015. Secondary metabolites of plants and their role: Overview. Current trends in biotechnology and pharmacy, 9(3): 293-304.

Pant P, Pandey S, Dall'Acqua S. 2021. The influence of environmental conditions on secondary metabolites in medicinal plants: A literature review. In Chemistry and Biodiversity, 18(11). John Wiley and Sons Inc. https://doi.org/10.1002/cbdv.202100345

Patel RM, Patel KH, Adhvaryu MR. 2024. Enhancement of secondary metabolite production in tinospora cordifolia suspension cultures using gibberellic acid elicitation: A Comprehensive analysis of alkaloids and phenols. International Journal of Innovative Science and Research Technology (IJISRT), 910–917.

https://doi.org/10.38124/ijisrt/ijisrt24nov500

Patil M, Sharma S, Sridhar K, Anurag RK, Grover K, Dharni K, Mahajan S, Sharma M. 2024. Effect of postharvest treatments and storage temperature on the physiological, nutritional, and shelf-life of broccoli (*Brassica oleracea*) microgreens. Scientia Horticulturae, 327. https://doi.org/10.1016/J.SCIENTA.2023.112805

Purba T, Situmeang R, Rohman HF, Mahyati, Arsi, Firgiyanto R, Junaedi AS, Saadah TT, Junairiah, Herawati J, Suhastyo AA. 2021. Pemupukan dan Teknologi Pemupukan. In R. Watrianthos (Ed.), Yayasan Kita Menulis (1st ed.).

Putri EA, Rahmadhia SN, Septiyani R. 2024. Estimation of the shelf life of wedang uwuh ready to drink with blanching and non blanching treatments. Jurnal Al-Azhar Indonesia Seri Sains dan Teknologi, 9(1). https://doi.org/10.36722/sst.v9i1.2133

Rahayu YYS, Araki T, Rosleine D. 2020. Factors affecting the use of herbal medicines in the universal health coverage system in Indonesia. Journal of Ethnopharmacology, 260. https://doi.org/10.1016/j.jep.2020.112974

Rahimi A, Gitari H, Lyons G, Heydarzadeh S, Tuncturk M, Tuncturk R. 2023. Effects of vermicompost, compost and animal manure on vegetative growth, physiological and antioxidant activity characteristics of *Thymus vulgaris* L. under water stress. Yuzuncu Yil University Journal of Agricultural Sciences, 33(1): 40–53. https://doi.org/10.29133/yyutbd.1124458

Rajput MS, Nirmal NP, Nirmal SJ, Santivarangkna C. 2022. Bio-actives from *Caesalpinia sappan* L.: Recent advancements in phytochemistry and pharmacology. South African Journal of Botany, 151: 60–74. https://doi.org/10.1016/j.sajb.2021.11.021

Raptania CN, Zakia S, Fahira AI, Amalia R. 2024. Article review: Brazilin as potential anticancer agent. Frontiers in Pharmacology, 15: 1-9. Frontiers Media SA. https://doi.org/10.3389/fphar.2024.1355533

Rosniawaty S, Ariyanti M, Mubarok S, Sudirja R, Rachman AL, Septiani D, Hamis ZM. 2025a. Impact of elicitor applications and planting distances on growth and phytochemical properties of Sappanwood (*Caesalpinia sappan* L.). Research on Crops, 26(1): 132-137. https://doi.org/10.31830/2348-7542.2025.ROC-1152

Rosniawaty S, Bahjatien ID, Soleh MA, Ariyanti M, Sudirja R. 2024b. Potensi metil jasmonat dan asam salisilat sebagai elisitor dalam mempengaruhi pertumbuhan bibit tanaman secang (*Caesalpinia sappan* L.). Agroland, 31(1): 55–62.

Rosniawaty S, Prasasta FP, Ariyanti M, Anjarsari IRD, Soleh MA, Mubarok S, Sudirja R. 2024c. Effect of crop pattern and types of manure on the growth of Sappan wood (*Caesalpinia Sappan* L.) in Jatinangor, West Java, Indonesia. Research on Crops, 25(1): 122–127. https://doi.org/10.31830/2348-7542.2024.ROC-1042

Rosniawaty S, Anjarsari IRD, Sudirja R, Mubarok S, Fatmawati D. 2023d. Effect of growth regulators and organic matter on the growth of Sappan wood seedlings (*Caesalpinia sappan* L.). Research on Crops, 24(1): 198–209. https://doi.org/10.31830/2348-7542.2023.ROC-896

Rosniawaty S, Al-Adawiah AR, Mubarok S, Sudirja R, Ariyanti M. 2023e. Respons pertumbuhan akar bibit secang (*Caesalpinia sappan* L.) di dataran rendah terhadap sitokinin dan giberelin. Agrisaintifika, 7(1).

Rupngam T, Udomkun P, Boonupara T, Kaewlom P. 2025. Enhancing soil health, growth, and bioactive compound accumulation in sunflower sprouts using agricultural byproduct-based soil amendments. Agronomy, 15: 1-33. https://doi.org/10.3390/agronomy15051213

Sakti AS, Saputri FC, Mun'im A. 2019. Optimization of choline chloride-glycerol based natural deep eutectic solvent for extraction bioactive substances from *Cinnamomum burmannii* barks and *Caesalpinia sappan* heartwoods. Heliyon, 5: 1-9. https://doi.org/10.1016/j.heliyon.2019.e02915

Sanam SC, Marzvan S, Khiavi SJ, Rahimi M. 2020. Changes in growth, biochemical, and chemical characteristics and alteration of the antioxidant defense system in the leaves of tea clones (*Camellia sinensis* L.) under drought stress. Scientia Horticulturae, 265: 1-10.

https://doi.org/10.1016/j.scienta.2020.109257

Sarwar M, Patra JK, Ali A, Maqbool M, Arshad MI. 2020. Effect of compost and NPK fertilizer on improving biochemical and antioxidant properties of *Moringa oleifera*. South African Journal of Botany, 129: 62–66. https://doi.org/10.1016/j.sajb.2019.01.009

Septiani D, Suryadi H, Mun'im A. 2022. Improving enzyme-assisted extraction of brazilin from Sappanwood (*Caesalpinia Sappan* L.) extract by fungal cellulase. Pharmacognosy Journal, 14(1): 21–28. https://doi.org/10.5530/pj.2022.14.4

Septiyani R, Wikandari R, Santoso U, Raharjo S. 2024. Brazilin content, color stability, and antioxidant activity of sappan wood (*Caesalpinia Sappan* L.) traditional drink by different blanching and drying methods. Trends in Sciences, 21(12). https://doi.org/10.48048/tis.2024.8535

Settharaksa S, Monton C, Charoenchai L. 2019. Optimization of *Caesalpinia sappan* L. heartwood extraction procedure to obtain the highest content of brazilin and greatest antibacterial activity. Journal of Integrative Medicine, 17(5): 351–358. https://doi.org/10.1016/j.joim.2019.05.003

Setyowati N, Masyhuri, Mulyo JH, Irham, Yudhistira B. 2023. The hidden treasure of wedang uwuh, an ethnic traditional drink from Java, Indonesia: Its benefits and innovations. International Journal of Gastronomy and Food Science, 31. https://doi.org/10.1016/j.ijgfs.2023.100688

Singh J, Mirza A, Singh S, Singh P. 2017a. Impact of phytohormons on physyio-chemical properties of tropical and subtropical fruits: A review. Plant Archives, 18(1): 12–18.

Singh R, Singh S, Parihar P, Mishra RK, Tripathi DK, Singh V., Chauhan DK, Prasad SM. 2016b. Reactive oxygen species (ROS): Beneficial companions of plants' developmental processes. In Frontiers in Plant Science, 7: 1-19. Frontiers Media S.A. https://doi.org/10.3389/fpls.2016.01299

Srisaikham S, Rupitak Q. 2020. Growth of *Caesalpinia sappan* L. by using different growing media and evaluation of antioxidant activity of foliage. Science Technology and Engineering Journal (STEJ), 6(2): 50–61. https://stej.msu.ac.th/wp-content/uploads/2021/01/JOURNAL-STEJ6-2-0005-56-67.pdf

Tamburini D. 2019. Investigating Asian colourants in Chinese textiles from Dunhuang (7th-10th century AD) by high performance liquid chromatography tandem mass spectrometry – Towards the creation of a mass spectra database. Dyes and Pigments, 163: 454–474. https://doi.org/10.1016/j.dyepig.2018.12.025

Thanayutsiri T, Patrojanasophon P, Opanasopit P, Ngawhirunpat T, Laiwattanapaisal W, Rojanarata T. 2023. Rapid and efficient microwave-assisted extraction of *Caesalpinia sappan* Linn. heartwood and subsequent synthesis of gold nanoparticles. Green Processing and Synthesis, 12:1–9. https://doi.org/10.1515/gps-2022-8109

Thiyageshwari S, Gayathri P, Krishnamoorthy R, Anandham R, Paul D. 2018. Exploration of rice husk compost as an alternate organic manure to enhance the productivity of blackgram in typic haplustalf and typic rhodustalf. International Journal of Environmental Research and Public Health, 15: 1-14. https://doi.org/10.3390/ijerph15020358

Torun H, Novák O, Mikulík J, Pěnčík A, Strnad M, Ayaz FA. 2020. Timing-dependent effects of salicylic acid treatment on phytohormonal changes, ROS regulation, and antioxidant defense in salinized barley (*Hordeum vulgare* L.). Scientific Reports, 10(1): 1–17. https://doi.org/10.1038/s41598-020-70807-3

Tu WC, Ding LF, Peng LY, Song LD, Wu X-De, Zhao QS. 2022. Cassane diterpenoids from the seeds of *Caesalpinia bonduc* and their nitric oxide production and α-glucosidase inhibitory activities. Phytochemistry, 193: 1-11. https://doi.org/10.1016/j.phytochem.2021.112973

Twaij BM, Hasan MN. 2022. Bioactive secondary metabolites from plant sources: Types, synthesis, and their therapeutic uses. International Journal of Plant Biology, 13(1): 4–14. https://doi.org/10.3390/ijpb13010003

Uddin GM, Kim CY, Chung D, Kim KA, Jung SH. 2015. One-step isolation of sappanol and brazilin from Caesalpinia sappan and their effects on oxidative stress-induced retinal death. BMB Reports, 48(5) :289–294. https://doi.org/10.5483/BMBRep.2015.48.5.189

Utari FD, Sari DA, Kurniasari L, Kumoro AC, Djaeni M, Hii CL. 2023. The enhancement of sappanwood extract drying with foaming agent under different temperature. AIMS Agriculture and Food, 8(1): 214–235. https://doi.org/10.3934/AGRFOOD.2023012

Vij T, Anil PP, Shams R, Dash KK, Kalsi R, Pandey VK, Harsányi E, Kovács B, Shaikh AM. 2023. A comprehensive review on bioactive compounds found in *Caesalpinia sappan*. Molecules, 28: 1-22. Multidisciplinary Digital Publishing Institute (MDPI). https://doi.org/10.3390/molecules28176247

Wang J, Song L, Gong X, Xu J, Li M. 2020a. Functions of jasmonic acid in plant regulation and response to abiotic stress. International Journal of Molecular Sciences, 21: 1-17. https://doi.org/10.3390/ijms21041446

Wang P, Liu WC, Han C, Wang S, Bai MY, Song CP. 2024b. Reactive oxygen species: Multidimensional regulators of plant adaptation to abiotic stress and development. In Journal of Integrative Plant Biology, 66(3): 330-367. John Wiley and Sons Inc. https://doi.org/10.1111/jipb.13601

Wani SH, Kumar V, ShriramV, Sah SK. 2016. Phytohormones and their metabolic engineering for abiotic stress tolerance in crop plants. Crop Journal, 4(3): 162–176. https://doi.org/10.1016/j.cj.2016.01.010

Waszczak C, Carmody M, Kangasjärvi J. 2018. Reactive oxygen species in plant signaling. Annual Review of Plant Biology, 1: 209–236. https://doi.org/10.1146/annurev-arplant-042817

Wudtiwai B, Kodchakorn K, Shwe TH, Pothacharoen P, Phitak T, Suninthaboonrana R, Kongtawelert P. 2023. Brazilein inhibits epithelial-mesenchymal transition (EMT) and programmed death ligand 1 (PD-L1) expression in breast cancer cells. International Immunopharmacology, 118: 1-12. https://doi.org/10.1016/j.intimp.2023.109988

Wyk ASV, Prinsloo G. 2020. Health, safety and quality concerns of plant-based traditional medicines and herbal remedies. In South African Journal of Botany, 133: 54-62. Elsevier B.V. https://doi.org/10.1016/j.sajb.2020.06.031

Xuan Q, Zhou JF, Jiang F, Zhang W, Wei A, Zhang W, Zhang Q, Shen H, Li H, Chen C, Wang P. 2022. Sappanwood-derived polyphenolic antidote of amyloidal toxins achieved detoxification via inhibition/ reversion of amyloidal fibrillation. International Journal of Biological Macromolecules, 214: 446–458. https://doi.org/10.1016/j.ijbiomac.2022.06.141

Yan X, Xu L, Qi C, Chang Y, Zhang J, Li N, Shi B, Guan B, Hu S, Huang C, Wang H, Chen Y, Xu X, Lu J, Xu G, Chen C, Li S, Chen Y. 2025. Brazilin alleviates acute lung injury via inhibition of ferroptosis through the SIRT3/GPX4 pathway. Apoptosis, 30: 768–783. https://doi.org/10.1007/S10495-024-02058-W/METRICS

Yang L, Wen KS, Ruan X, Zhao YX, Wei F, Wang Q. 2018. Response of plant secondary metabolites to environmental factors. In Molecules, 23: 1-26. MDPI AG. https://doi.org/10.3390/molecules23040762

Zhang J, Shoaib N, Lin K, Mughal N, Wu X, Sun X, Zhang L, Pan K. 2024. Boosting cadmium tolerance in *Phoebe zhennan*: The synergistic effects of exogenous nitrogen and phosphorus treatments promoting antioxidant defense and root development. Frontiers in Plant Science, 15: 1-17. https://doi.org/10.3389/fpls.2024.1340287

Zhao B, Liu Q, Wang B, Yuan F. 2021. Roles of phytohormones and their signaling pathways in leaf development and stress responses. Journal of Agricultural and Food Chemistry, 69(12): 3566–3584. https://doi.org/10.1021/acs.jafc.0c0790

Zhu NL, Sun ZH, Hu MG, Wu TY, Yuan JQ, Wu HF, Tian Y, Li PF, Yang JS, Ma GX, Xu XD. 2017. New cassane diterpenoids from *Caesalpinia sappan* and their antiplasmodial activity. Molecules, 22(10). https://doi.org/10.3390/molecules22101751