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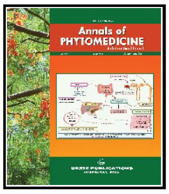

Review Article : Open Access

# Unveiling the marvels of *Pterocarpus*: Traditional wisdom, phytochemistry and potent antimicrobial action

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**Abstract**

Plants serve as crucial nutrient providers and significantly contribute to human well-being, with approximately 80% of people depending on medicinal plants. The summary concisely outlines the significance of *Pterocarpus* species in terms of their phytochemical and pharmaceutical value. The genus *Pterocarpus*, involves 45 to 60 species, out of which 35 species are accepted. *Pterocarpus* species includes *Pterocarpus santalinus*, *Pterocarpus marsupium* and *Pterocarpus indicus*, which are rich in bioactive compounds, has garnered attention for its diverse pharmacological properties. This review explores the phytochemical constituents of *Pterocarpus* species, underscoring the existence of flavonoids, terpenoids, alkaloids, and other phytochemicals. Emphasis is placed on the potential pharmaceutical applications, including antifungal, antiviral, and antibacterial activities. The synergistic interaction of these compounds contributes to the therapeutic efficacy observed in traditional medicinal uses and encourages further research like phytochemical analysis, ethnopharmacology and clinical trial for the development of novel drugs and therapeutic interventions.

## 1. Introduction

Plants have long served as a rich reservoir of bioactive compounds, extensively utilized for their medicinal properties across diverse regions worldwide (Ahad *et al*., 2021). Through intricate primary and secondary metabolic processes, plants offer a spectrum of therapeutic benefits, both approved and unapproved, spanning various plant phyla (Rahman *et al*., 2018; Rai *et al*., 2023). Over 80% of the global population continues to depend on plant resources, particularly in developing and impoverished countries (Jeurkar *et al*., 2022). In recent years, there has been a notable surge in the utilization of medicinal plants for the production of pharmaceuticals, phytochemicals, nutraceuticals, cosmetics, and allied products, reflecting a growing recognition of their therapeutic potential (Santhosha and Mohan, 2023).

Medicinal plants, comprising botanical species harboring active compounds, have historically played a pivotal role in traditional medical systems across civilizations worldwide (Khan *et al*., 2023). Particularly in India, where three prominent traditional medical systems; namely, Ayurveda, Siddha, and Unani, have flourished, indigenous populations and traditional healers extensively rely on the therapeutic properties of plants to address a myriad of health concerns (Seetharamu *et al*., 2023). The rich biodiversity of India's forests, teeming with a wide array of medicinal plant species, stands as a testament to nature's gift to humanity, offering invaluable resources for healthcare and well-being (Londonkar and Hugar, 2017).

The World Health Organization (WHO) recognizes the significance of folk medicine in member countries, advocating for its integration into healthcare systems for both the treatment and prevention of diseases (Bamne *et al*., 2023). Amidst this backdrop, the genus *Pterocarpus*, belonging to the family Fabaceae, emerges as a focal point of inquiry, characterized by a diverse assemblage of flowering trees and shrubs distributed internationally across warm temperate to subtropical regions. Various plant parts of this genus, such as bark, leaves, roots, and fruits, have been used in folk medicine for their therapeutic value (Figure1). Renowned for their valuable timber and the therapeutic compounds found within their heartwood, *Pterocarpus* species have made enduring contributions to traditional medicine, leaving an indelible mark on ecosystems and cultures worldwide.

Distinguished by compound leaves and leguminous flowers, *Pterocarpus* species are renowned for their exceptional heartwood, often exhibiting vibrant hues such as red, pink, or purple. Commonly referred to as red sandalwood, Indian Kino, Burmese rosewood, and Andaman redwood, among other names, this distinctive heartwood holds significant economic and cultural value. Widely utilized in furniture, construction, and artistic endeavors, the durability and aesthetic appeal of *Pterocarpus* timber have fueled its demand across

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industries. However, this demand has also spurred challenges such as illegal logging and habitat degradation, necessitating concerted conservation efforts to ensure the sustainable utilization of these invaluable resources. Thus, understanding the traditional wisdom, phytochemistry, and potent antimicrobial properties of *Pterocarpus* species assumes critical importance, not only for unlocking their therapeutic potential but also for safeguarding their ecological and cultural significance.

**Figure 1: Leaf and bark of *P. marsupium*, *P. indicus* and *P. santalinus*.**

## 2. Traditional uses

The genus *Pterocarpus*, comprising around 46 species, offers a diverse array of medicinal benefits, as summarized in Table 1. *Pterocarpus angolensis*, for instance, finds historical use in ancient medicine, being employed to alleviate headaches, mouth ulcers, and various ailments such as malaria, gonorrhea, schistosomiasis, and blackwater fever through the decoction of its bark (Teclegeorgish *et al*., 2024).Additionally, the alcohol extract of *Pterocarpus rohrii* bark serves medicinal purposes as a tonic, wound healer, and antimalarial remedy. *Pterocarpus macrocarpus* Kurz. stands out for its medicinal attributes in combating Alzheimer's disease, alongside its recognized benefits in alleviating spasms, combating cancer, and addressing malaria,which typically inhibit the growth and development of the parasites, disrupting their life cycle and preventing their proliferation within the host's body, whereas antispasmodic effects can occur through the modulation of neurotransmitters or ion channels involved in muscle contraction, leading to the inhibition of excessive muscle activity (Wahyuni *et al*., 2023).

*P. marsupium, P. indicus, P. santalinus, Pterocarpus dalbergioides, Pterocarpus osun,* and *Pterocarpus erinaceus*, are extensively utilized in folk medicine. They are utilized in addressing various ailments like cancer sores, scabies, nose bleeds, inflammatory diseases, gonorrhea, mouth ulcers, diarrhea, skin diseases, eye diseases, urinary complaints, tuberculosis, typhoid fever, malaria, anemia, rheumatism, gastrointestinal problems, eczema, sickle-cell diseases, mental disorders, and limb paralysis. Moreover, their decoctions have been utilized for managing blood sugar levels, reducing complications of hyperglycemia, and exhibiting antidiabetic, antiglycation, and rasayana properties. Recent applications also include the use of herbal teas and pills to alleviate menstrual pain, leprosy, flu, and diabetes (Thomson, 2006; Nadembega *et al*., 2011; Katiyar *et al*., 2016; Ezeani *et al*., 2017; Rahman *et al*., 2018; Mondal and Landge, 2019; Ouinsavi *et al*., 2021; Fadeyi *et al*., 2022; Fadeyi *et al*., 2023; Fadeyi and Adeniran, 2023).

**Table 1: Traditional uses of different *Pterocarpus* species**

| S. No. | Species | Parts | Mode of usage | Medicinal use | Reference |
|---|---|---|---|---|---|
| 1. | *P. angolensis* | Bark | Decoction | Malaria, gonorrhea, black water fever, and schistosomiasis | Teclegeorgish *et al.*, 2024 |
| 2. | *P. erinaceus* | Leaves, stem bark, root | - | Inflammation, ulcers, pain in the joints, malarial fever, and bacterial infections | Mohammed *et al.*, 2023 |
| 3. | *P. indicus* | Leaf, wood, bark, root | Decoction or crude extract | Urinary tract stones, loose stools, dysentery, mouth ulcers, and syphilis lesions | Retnosari *et al.*, 2023 |
| 4. | *P. macrocarpus* | Bark | Crushed and applied to mouth | Sore teeth, anticancer, antimalarial, antispasmodic, and Alzheimer's disease | Khuankaew *et al.*, 2014; Wahyuni *et al.*, 2023 |
| 5. | *P. marsupium* | Wood | - | Skin diseases, diabetes, diarrhoea, asthma, bronchitis, and digestive issues following childbirth | Biswas *et al.*, 2017; Pari *et al.*, 2018 |
| 6. | *Pterocarpus mildbraedii* | Leaf | Leaf extract | Headaches, pains, fever, convulsions, and respiratory disorders | Akinyeye *et al.*, 2010 |
| | | Stem bark | Ground into a paste and administered topically | Rheumatism | Ekpo *et al.*, 2008 |
| 7. | *P. osun* | Powdered stem | Applied topically | Sprains, rheumatic complaints, and skin diseases | Ebi and Ofoefule, 2000 |
| 8. | *P. rohrii* | Bark | Decoction | Tuberculosisand health tonic | Sanz-Biset *et al.*, 2009 |
| 9. | *P. santalinus* | Leaves | Decoction | Miasma, boils, inflammation, infection, and headache | Odoh *et al.*, 2018 |
| | | Fruit | Decoction | Blood vomiting, hallucinations, weak vision, andchronic dysentery | Arunakumara *et al.*, 2011 |
| 10. | *Pterocarpus santalinoides* | Root, leaf | Decoction and water maceration taken twice daily | Tiredness, diarrhoea | Igoli *et al.*, 2005; Allabi *et al.*, 2011 |
| 11. | *Pterocarpus soyauxii* | Bark | Crushing and water maceration | Body careand hair coloring | Fongnzossie *et al.*, 2017 |

## 3. Phytochemistry

Phytochemicals, the diverse compounds synthesized by plants through primary and secondary metabolites, play pivotal roles in various biological activities (Balamurugan *et al.*, 2019). Derived from different plant parts, phytomedicines serve as essential components with widespread applications in pharmaceutical, and herbal industries, contributing significantly to drug discovery (Londonkar and Hugar, 2017). Notably, flavonoids emerge as prominent constituents significantly influencing the biological activity of *Pterocarpus* species (Alnusaire *et al.*, 2023). Figure 2 illustrates the chemical structures of these compounds present in *Pterocarpus* species.

### 3.1 Pterocarpans

Pterocarpans, a class of isoflavonoid compounds primarily found in plants, exhibit antioxidant, antimicrobial, and anticancer activities. The presence of hydroxyl substituents on the pterocarpan nucleus has been found to enhance their antioxidant activity (Arora *et al.*, 1998). (-)- homopterocarpin is an isoflavonoid compound isolated from the stem bark of *P. erinaceus*. It has been investigated for its protective properties against acetaminophen-induced oxidative stress and liver damage in rats, showing potential as a hepatoprotective and antioxidant agent. It is also evaluated for its antifungal activity against phytopathogenic fungi such as *Colletotrichum gloeosporioides* and *C. lindemuthianum*, which are causal agents of anthracnose in various crops (Olaleye *et al.*, 2013; Martinez *et al.*, 2023).

### 3.2 Flavonoids

Flavonoids, secondary metabolites synthesized by plants, feature variable phenolic structures with potential applications in medicinal chemistry. Most *Pterocarpus* species contain flavonoids. For example, quercetin, a polyphenolic flavonoid found naturally (Arif *et al.*, 2022), found in the leaves and stem bark of *P. osun*, exhibits potential health benefits such as antioxidant protection, antimicrobial activity,and efficacy against stress-related illnesses. The antioxidant properties of quercetin are attributed to its ability to scavenge free radicals and reduce oxidative stress in the body. It also demonstrates the capability to hinder lipid peroxidation and shield cells from oxidative harm. Moreover, quercetin exhibits antimicrobial properties against various pathogens, comprising bacteria and fungi, by disrupting microbial cell membranes, impeding microbial enzyme activity, and interfering with microbial DNA replication and protein synthesis (Fadeyi and Adeniran, 2023). Additionally, liquiritigenin is reported in *P. soyauxii* (Su *et al.,* 2013). Quercetin effectively hinders various bacterial strains, such as *Enterococcus faecalis, Staphylococcus aureus, Streptococcus mutans, Escherichiacoli*, and *Pseudomonas aeruginosa*. Additionally, when quercetin is used alongside bacterial combinations, it notably reduces Fusarium wilt disease and improves plant growth characteristics to the greatest extent (Memariani *et al*., 2019; Hassan *et al*., 2023).

### 3.3 Polyphenols

Plants contain a diverse array of polyphenols, renowned for their anti-inflammatory and antioxidant characteristics (Pandey and Rizvi, 2009). Pterostilbene, a polyphenol reported in the seed of *P. santalinus* and the heart wood of *P. marsupium,* possesses antitumorigenic, antioxidant, antiinflammatory, and antiaging effects and also exhibits antifungal activity against *Saccharomyces cerevisiae* (Akhouri*et al*., 2020; Majeed *et al*., 2020; Mizuhara *et al*., 2023).

### 3.4 Isoflavonoids

Pterolinus B, pterolinus K, and pterolinus L are reported to be present within *P. santalinus*. *P. erinaceus* contains compounds such as muningin, formononetin, pseudobaptigenin, boutomycone, boutotone, and calycosin. Additionally, a specific isoflavonoid compound known as 7-O-α-L-rhamnopyranosyl-oxy-42 -methoxy-5-hydroxy isoflavone is located in the heartwood of *P. marsupium* (Anandharajan *et al*., 2005; Toukam *et al*., 2018; Tittikpina *et al*., 2019; Akhouri *et al*., 2020).

### 3.5 Epicatechin

Epicatechin, a flavanol and plant-based polyphenolic molecule, exhibits various biological activities, including antioxidant, antiinflammatory, cardioprotective, and neuroprotective (Ananingsih *et al*., 2013; Ramirez-Sanchez *et al*., 2014). In *P. erinaceus*, epicatechin-3-O-galate demonstrates antimicrobial and antiinflammatory properties (Noufou *et al*., 2012). Additionally, epicatechin 5-O-beta-D-glucopyranoside-3-benzoate is reported in *P. dalbergioides* (Alnusaire *et al*., 2023). (-)-epicatechin and epicatechin (4-β-8)-epicatechin (B2) are reported in *P. angolensis* (Teclegeorgish *et al*., 2024).

### 3.6 Sesquiterpenoids

Sesquiterpenoids, comprising three isoprene units, are naturally occurring chemicals present in various plant species, offering a diverse spectrum of biological actions, including antioxidant, antibacterial, and antiswellingattributes (Chadwick *et al*., 2013). Isolates from the heartwood of *P. santalinus* such as pterocarpol, canusesnol K, canusesnol L, and 12, 15-dihydroxycurcumene exhibit cytotoxicity against melanoma cells (Li *et al*., 2018; Akhouri *et al*., 2020). Moreover, 3, 4, 9-trimethoxypterocarpan have been isolated from *P. dalbergioides* (Alnusaire *et al*., 2023). Sesquiterpenoids obtained from seagrass exhibit weak antimicrobial activity against various pathogens (Hu *et al*., 2022).

### 3.7 Triterpenoids

Triterpenoids, characterized by their unique pentacyclic structure, are plant-derived compounds with significant therapeutic values (Dzubak *et al*., 2006). Isolates from the bark of the stem of *P. angolensis*, including friedelan-3-one, 3-hydroxyfriedel-2-one, 3α-hydroxyfriedel-3-en-2one, (3β)-lup-20(29)-en-3-ol, stigmasta-5-22-dien-3-ol, and (3β)-3-acetoxyolean-12-en-28-oic acid, are reported to possess anticarcinogenic properties (Teclegeorgish *et al*., 2024).

### 3.8 Sterols

*P. erinaceus* and *P. santalinus* yield sterols like β-sitosterol, stigmasterol, campesterol, and stigmasterol glucoside (Tittikpina *et al*., 2018; Toukam *et al*., 2018; Akhouri *et al*., 2020).

### 3.9 Phenolic Acids

Phenolic acids, which belong to the group of polyphenols present in diverse plants, demonstrate notable antioxidant and antimicrobial characteristics (Tsao, 2010). The bark of *P. dalbergioides* contains two compounds, 5-hydroxysalicylic acid and 3,4,5-trihydroxybenzoic acid, that exhibit properties that reduce inflammation and lower blood sugar levels (Michel *et al*., 2013). Gallic acid, another phenolic acid reported in *P. osun*, acts as a source of natural antioxidants and shows resistance to numerous harmful bacteria like *E. coli*, *P. aeruginosa, S. aureus, Listeria monocytogenes*, and *Alternaria solani* (Borges *et al*., 2013; El-Nagar *et al*., 2020).

### 3.10 Coumarins

Coumarins, secondary metabolites present in higher plants, microorganisms, and animal species, derive their name from the plant *Coumarouna odorata*. They play a crucial role against various plant pathogens, including *Phytophthora megasperma, Ralstonia solanacearum*, and *Sclerotinia sclerotiorum* (Stringlis *et al*., 2019). Coumarins extracted from the ethyl acetate extract of *P. indicus* comprise phebalosin and indicusane (Sichaem *et al*., 2016). Identified coumarins in *P. santalinus* consist of 5-hydroxy-7-O-(3-methyl)-but-2-enylcoumarin, 6-hydroxy-7-methoxy-2H-chromen-2-one, and 3-aryl coumarin, which are beneficial in managing conditions like high-protein edema (HPE) and other persistent infections (Azamthulla *et al*., 2016; Pullaiah *et al*., 2019). Coumarinsalso been identified in the trunk and root bark of *P. santalinoides* (Ayéna *et al*., 2022).

### 3.11 Lignans

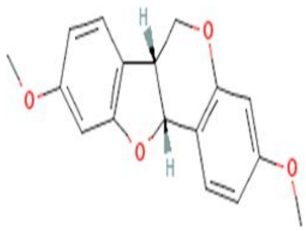
Lignans, a vast class of naturally occurring substances produced *via* the shikimic acid biosynthesis pathway, possess a wide range of therapeutic values (Cui *et al*., 2020). The heartwood of *P. santalinus* produces lignans like savinin, calocedrin, pterolinus A, pterolinus B, pterolinus D, and dehydromelanoxin, which demonstrate properties against inflammation and anticancer activities (Cho *et al*., 2001; Wu *et al*., 2011).

### 3.12 Fatty acids

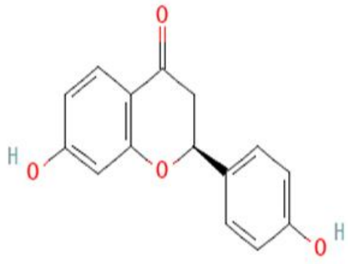
Plants produce a diverse array of lipid molecules, which are crucial for building the cellular structures of plants and supporting a variety of metabolic functions (Ohlrogge and Browse, 1995). *P. dalbergioides* yields five fatty acids, including heptadecanoic acid, 9-octadecenedioic acid, 9,10,11-trihydroxy-12,15-octadecadienoic acid, and 11,12,13-trihydroxy-9-octadecenoic acid (Alnusaire *et al*., 2023).

Fatty acids are central in mediating plant-microbe interactions to combat a range of pathogens such as *A. solani, Colletotrichum lagenarium, Fusarium oxysporum* f. sp. *cucumerinum*, *Rhizoctonia solani, Pythium ultimum, Fusarium oxysporum* f. sp. *lycopersici*, *Pyrenophora avenae*, and *Crinipellis perniciosa* (Walters *et al*., 2004; Liu *et al*., 2008).

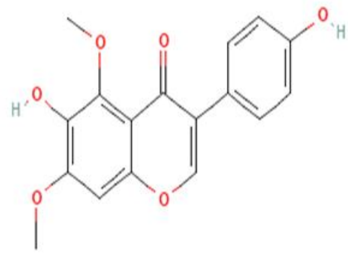
Additionally, Toukam *et al*. (2018) identified triacontanoic acid, dotriacontanoic acid, 2,3-dihydroxypropyl hexacosanoate, and octacosanoic acid in *P. angolensis*. Another plant species, *P. erinaceus*, has been reported to contain 2,3 dihydroxy propyloctacosanoate (Tittikpina *et al*., 2018). These findings underscore the presence of various fatty acid compounds in *P. angolensis* and *P. erinaceus*, which may contribute to their potential biological activities or applications.



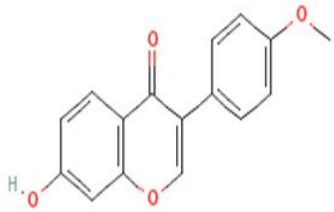
(-) - homopterocarpin



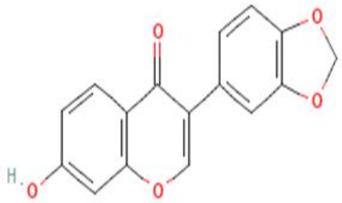
Liquiritigenin



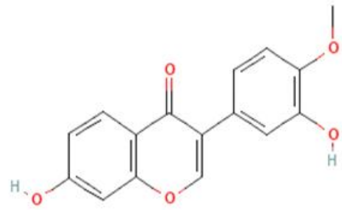
Muningin



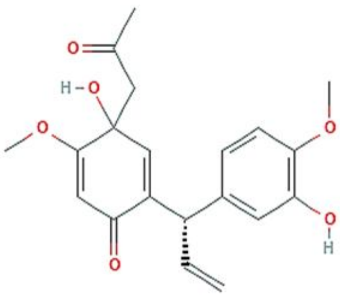
Formononetin



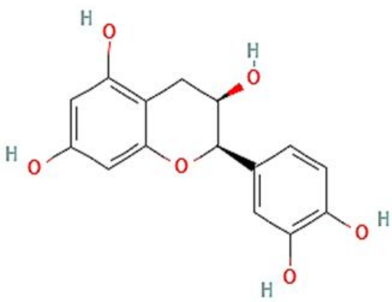
Pseudobaptigenin



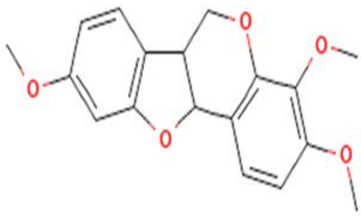
Calycosin



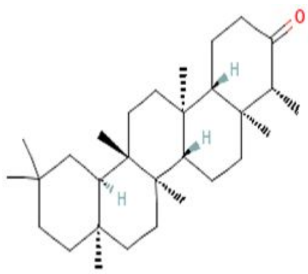
Pterolinus Ha, Hb



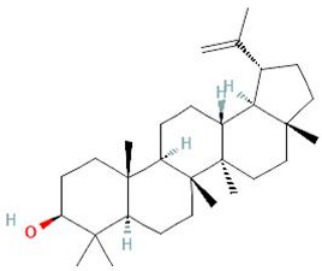
Epicatechin



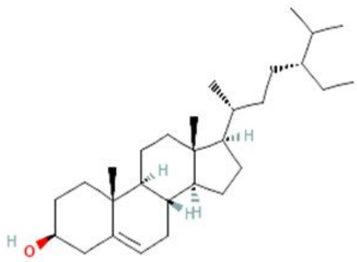
3, 4, 9-trimethoxypterocarpan



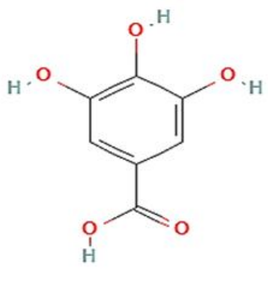
Friedelan-3-one



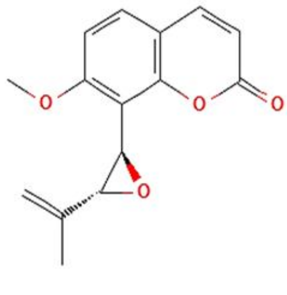
Lupeol



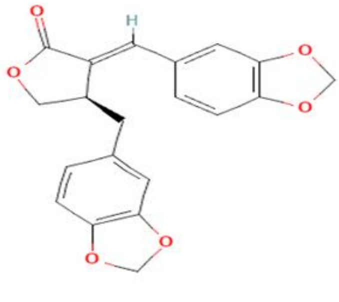
β-sitosterol



3,4,5-trihydroxybenzoic acid



Phebalosin



Savinin

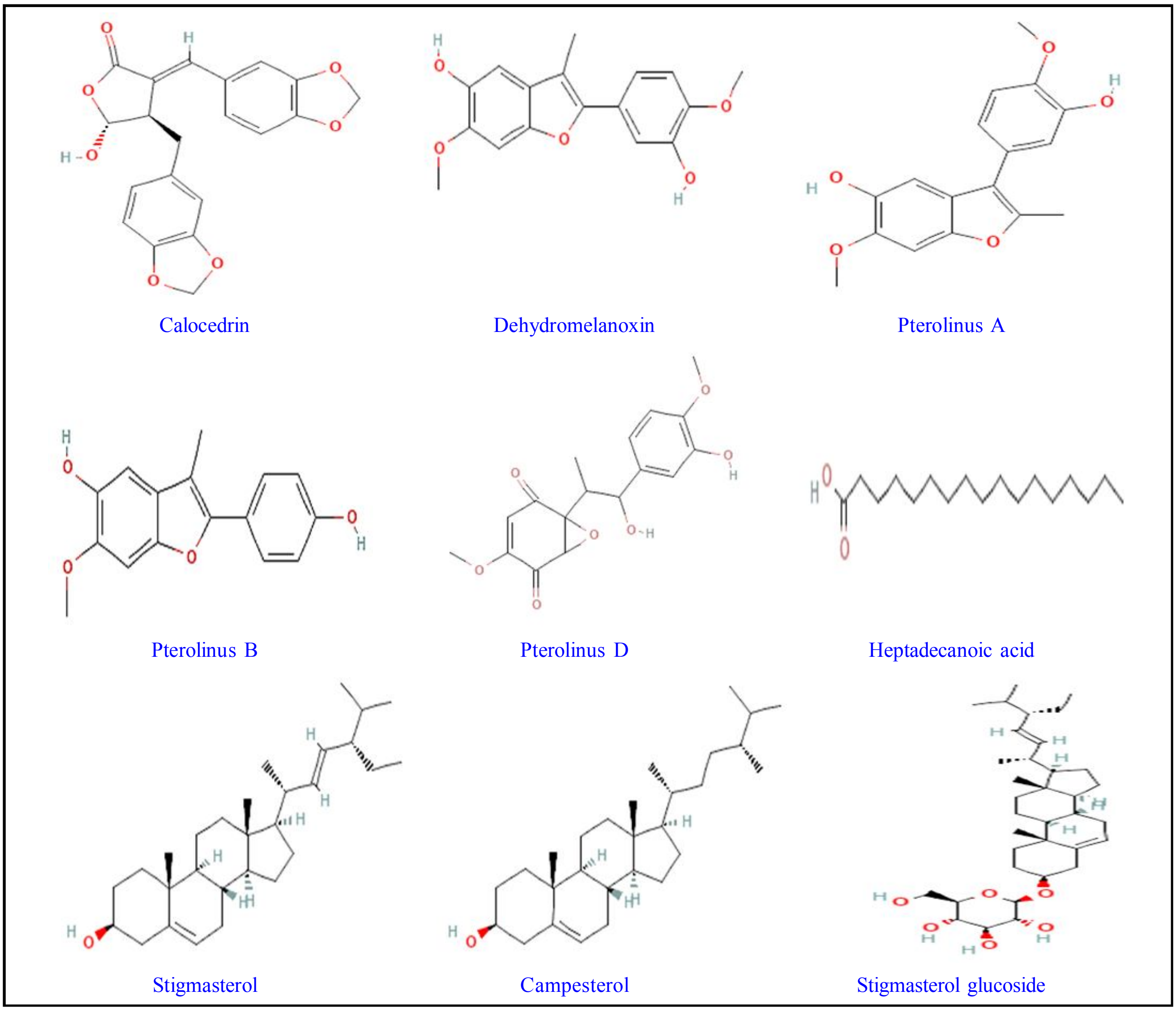



**Figure 2: 2D chemical structures of the compounds present in *Pterocarpus* species (Kim *et al*., 2023).**

## 4. Antimicrobial activity of *Pterocarpus*

### 4.1 Antiviral

Reports on the antiviral properties of *Pterocarpus* extracts are scarce. However, *P. indicus* extracts obtained from leaves using ethyl acetate have exhibited antiviral activity (Dewi *et al*., 2018). Further more, the compound furan-2-one, 3,4-dihydroxy-5-[1-hydroxy-2-fluoroethyl], a nucleoside derivative extracted from the bark of *P. marsupium*, exhibits antiviral activity as revealed by GC-MS analysis as mentioned in Figure 3 (Hugar and Londonkar, 2017).

### 4.2 Antifungal

Various compounds isolated from *P. erinaceus*, such as muningin, formononetin, pseudobaptigenin, boutomycone, boutotone, and the flavonoid isoliquiritigenin, have been found to inhibit the growth of fungi through diverse methods like RNA suppression, inhibition of protein synthesis, suppression of cell wall production, inhibition of cell division, and interference with efflux pump systems (Tittikpina *et al*., 2019). Moreover, these substances have been documented to hinder the proliferation of *Aspergillus fumigatus*, a fungus linked to respiratory issues, with minimum inhibitory concentrations spanning from 8 to 256 µg/ml (Tittikpina *et al*., 2019; Al Aboody and Mickymaray, 2020). Furthermore, the bark extract of *P. marsupium* demonstrated fungicidal effects against *Aspergillus niger* at a concentration of 25 µg/ml (Londonkar and Hugar, 2017) and showed beneficial effects against *Tinea cruris* and *Tinea corporis* (Katiyar *et al*., 2016).

### 4.3 Antibacterial activity

Recent research has thoroughly examined different compounds derived from plants belonging to the *Pterocarpus* for their antibacterial effects employing the disc diffusion technique. In this method, isolated compounds are loaded onto paper discs, which are then placed on agar plates inoculated with bacterial cultures. The diameter of the clear zone (inhibition zone) surrounding the disc after incubation serves as an indicator of the antibacterial potency of the tested compounds against specific bacterial strains. Generally, a larger inhibition zone diameter indicates stronger antibacterial activity exhibited by the compounds isolated from *Pterocarpus* species (Okoli *et al*., 2023).

The compounds epicatechin, lunamarin, ephedrine, and triterpenoids (such as friedelin and sterols) isolated from *P. erinaceus* exhibited inhibitory effects on *Bacillus cereus, S. aureus, E. faecalis, E. coli, P. aeruginosa, Pantoea agglomeran, Bacillus pumili, Bacillus subtilis*, and *Proteus mirabilis*, with minimum inhibitory concentration values ranging from 64 to 256 µg/ml (Samie *et al*., 2009; Odeh *et al*., 2016; Tittikpina *et al*., 2018; Okoli *et al*., 2022).

Extracts from the heartwood of *P. macrocarpus* Kurz. demonstrated antimicrobial activity against *B. substilis, S. aureus, E. coli*, and *Candida albicans* (Wahyuni *et al*., 2023). Similarly, *P. mildbraedii* stem extracts exhibited antimicrobial properties against *S. aureus, B. subtilis, P. aeruginosa, Salmonella typhi*, and *Klebsiella pneumoniae* (Odeja, 2023). Moreover, the hydroalcoholic extract of *P. santalinus* L. f. heartwood and leaf exhibited exceptional antimicrobial properties against *Taphylococcus aureus, Klebsiella pneumoniae, E. coli*, and *Helicobacter pylori* due to their phytochemical constituents (Verma and Devi, 2023).

Furthermore, specific compounds were isolated from *P.indicus*, such as 1-tricosanol, dodecane, and [bis(methylthio)methylene]acetyl]-2-(4-(4-methoxyphenyl)-1,3-butadienyl) exhibited antimicrobial and antifungal activities against pathogens like *E. coli, S. aureus,* and *B. subtilis* (Senthilkumar *et al*., 2020). Methanol extracts of *P. santalinus* (leaves and flowers) displayed significant antimicrobial potential against *P. aeruginosa, Streptococcus pneumonia, E. coli,* and *Salmonella enterica*, with maximum inhibition zones ranging from 24.0 to 38.6 mm (Bharathi and Prasad, 2020).

Additionally, *P. angolensis*, *P. macrocarpus*, and *P. soyauxii* inhibited the growth of the pathogens *Coriolus versicolor* and *Gloeophyllum trabeum* using deionized water and ethanol as solvents (Cai *et al*., 2019). Extracts of *P. marsupium* in acetone, methanol, and IPA showed maximum antimicrobial activity against *B. cereus, P. aeruginosa, Streptococcus pyrogens*, and *S. aureus* (Ramya*etal*., 2008; Londonkar and Hugar, 2017; Pant *et al*., 2017).

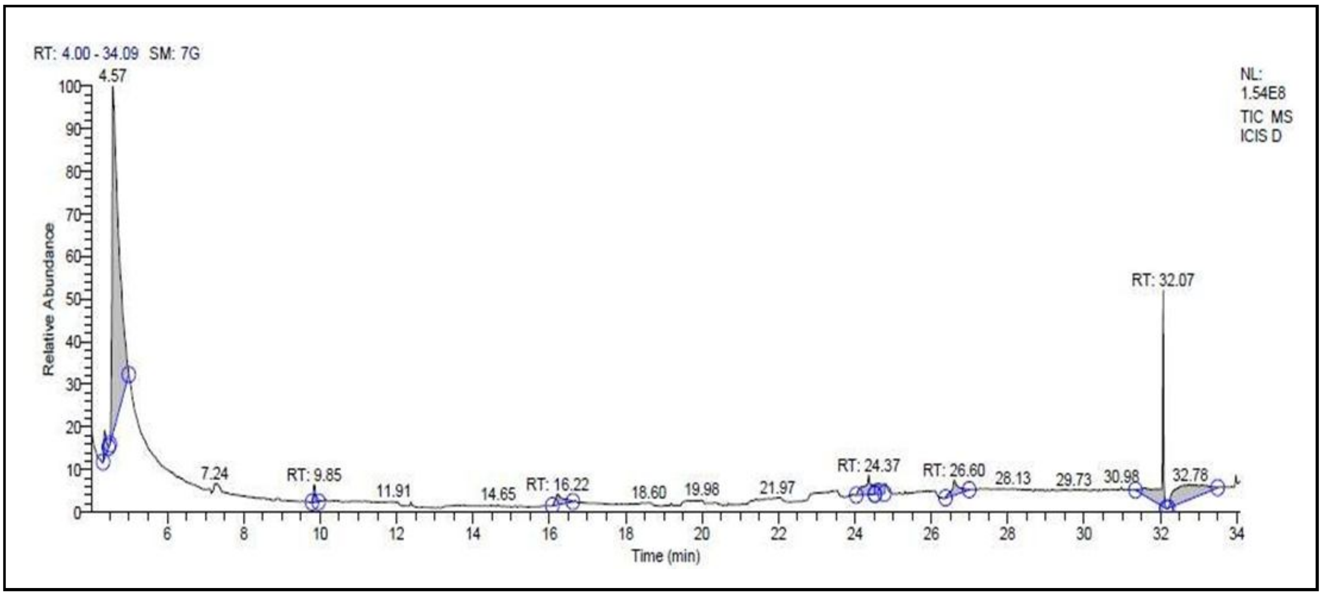



**Figure 3: GC-MS chromatogram of the aqueous extract of *P. marsupium* bark.**

## 5. Toxicological studies

Toxicological studies are essential for assessing the potential harmful effects of compounds on living organisms. In one study, the ethanolic leaf extract of *P. santalinus* underwent toxicological assessment to examine the consequences of subacute intake on various physiological parameters in Wistar rats. Administering the plant extract at doses of 100, 200, and 400 mg/kg led to a reduction in erythrocytes, red cell protein, and platelets at a dose of 100 mg/kg. Notably, there was also an impact on the mean corpuscular hemoglobin concentration. However, there were no significant alterations observed in the cerebrum, splenic organ, or gastric organ of the rats across all dosage groups, indicating the safety of the plant for consumption. Nevertheless, the study underscored the importance of exercising caution regarding long-term usage due to minor hematological effects (Joseph *et al*., 2024).

Similarly, another study employing the Lorke method evaluated the methanolic leaf extracts of *P. erinaceus* on albino rats. This result revealed that the extract was well-tolerated and safe for consumption, as there was no mortality or significant behavioral, respiratory, or somatomotor changes in rats at dosages of 1600 mg/kg, 2900 mg/kg, and 5000 mg/kg. Moreover, the extract did not induce any deaths or clinical signs of toxicity during the 28-day subacute toxicity study. Overall, it was concluded that doses up to 5000 mg/kg would be safe for human consumption and may offer potential health benefits, particularly in managing lipid profile-related conditions such as hypertension and diabetes (Folashade and Mary, 2021).

## 6. Clinical study

A clinical trial (Figure 4) was conducted on healthy individuals, both genders, ranging in age from 18 to 49 years, to evaluate the safety and potential health benefits of silbinol, a standardized extract from *P. marsupium* containing 90% pterostilbene. This trial was conducted using 60 healthy subjects over a period of 60 days. Three volunteers from the placebo group reported mild adverse events of fever and fatigue. However, these adverse events were mild and resolved. No other adverse events were reported by the participants, and no clinically significant biochemical changes were observed in either the *P. marsupium* extract or placebo groups during this study. Therefore, the study concluded that a dosage of 200 mg daily is considered suitable for human consumption (Majeed *et al*., 2023).

The efficacy of the natural pterostilbene (polyphenol) of *P. marsupium* was assessed in a clinical study. It involves *in vitro* evaluations of pterostilbene's activities, like melanogenesis inhibition, tyrosinase inhibition, collagenase inhibition, and elastase inhibition. This study was conducted on 38 healthy volunteers over 8 weeks and assessed parameters such as skin hydration, fine lines, wrinkles, elasticity, and skin tolerance. The results indicated significant improvement in hydration, skin brightness, and reduction in fine lines and wrinkles, with no adverse effects reported by the participants. Based on this study, a 0.4% formulation of pterostilbene cream was found to be well-tolerated and safe for consumer application (Majeed *et al*., 2020).

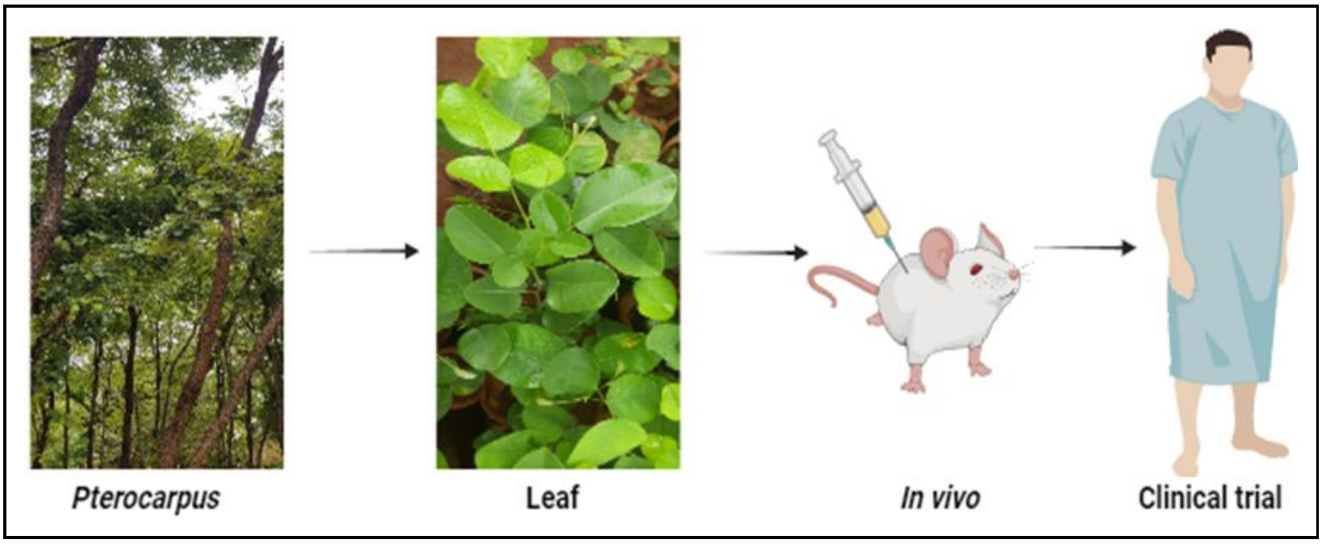



**Figure 4: Clinical trial illustration (created from BioRender.com).**

## 7. Recent applications

Recent studies have explored innovative applications of *Pterocarpus* species, showcasing their versatility in various fields. One notable application involves the green synthesis of magnesium oxide nanoparticles (MgO-NPs) using the heartwood aqueous extract of *P. marsupium*. Leveraging the extract's rich content of polyphenolic compounds and flavonoids, it serves as a green source for the large-scale synthesis of MgO-NPs. The successful synthesis of these nanoparticles was confirmed through various analyses, indicating their spherical shape, average size (< 20 nm), crystalline nature, and the presence of magnesium and oxygen. Moreover, the green-synthesized MgO nanoparticles demonstrated potent antibacterial action against both Gram-positive and Gram-negative bacteria, with minimum inhibitory concentrations ranging between 10-25 µg/ml. Additionally, they exhibited antioxidant, antidiabetic, and antiinflammatory activities, showcasing their potential for diverse applications. The antioxidant activity of MgO-NPs is attributed to their capacity to scavenge free radicals, as evidenced by their DPPH scavenging activity, which is facilitated by the presence of phenolic compounds, tannins, flavonoids, and other phytochemicals in the plant extract. In terms of antidiabetic activity, MgO-NPs inhibit the alpha-amylase enzyme, delaying starch breakdown into glucose and regulating glucose levels in diabetic patients, while also showing antidiabetic effects in hyperglycemic rats, potentially reversing insulin resistance. Furthermore, the antiinflammatory properties of MgO-NPs are linked to their ability to inhibit protein denaturation, leading to reduced inflammation in diabetic patients and demonstrating significant antiinflammatory activity by inhibiting paw edema, along with stronger analgesic and antiinflammatory effects in experimental tests. Overall, the diverse activities of MgO-NPs stem from their unique properties, including scavenging free radicals, inhibiting enzymes, and interacting with bacterial surfaces, making them promising for various biomedical applications (Ammulu *et al*., 2021).

Likewise, chitosan nanoparticles were synthesized using *P. marsupium* heartwood extract at varying concentrations. Of these concentrations, the nanoparticle containing 10% plant extract demonstrated ideal particle size, stability, entrapment efficiency, and sustained drug release properties. These chitosan nanoparticles exhibited notable antiinflammatory effects besides inhibition of alpha-amylase activity, a therapeutic target in controlling type 2 diabetes, as they helped reduce postprandial blood glucose spikes. These effects are attributed to the ability of nanoparticles to inhibit protein denaturation, which is a key process in the loss of biological characteristics of protein molecules. The anti-inflammatory activity of the nanoparticles tends to be an encouraging factor for developing drugs that can mitigate inflammatory disorders. Overall, the study suggests that the synthesized chitosan nanoparticles loaded with *P. marsupium* heartwood extract have the potential to be effective therapeutic agents against diabetes and inflammatory disorders (Manne *et al*., 2020).

## 8. Future trends and research needs

Medicinal plants, renowned for their therapeutic properties, are indispensable in addressing various health ailments. The demand for these plants is poised to increase globally, driven by both developing and industrialized nations, owing to their valuable contributions and population growth. Notably, medicinal plants not only cater to a vast array of healthcare needs but also serve as the primary source of certain medications in contemporary medicine.

Among the 46 species within the *Pterocarpus* genus, 35 are accepted and cultivated worldwide, yet only a limited number have undergone thorough scientific investigation. *P. marsupium, P. santalinus,* and *P. santalinoides* stand out as notable species within the genus that have garnered considerable attention and extensive research into their chemical composition. Therefore, there is a pressing need for further studies on the remaining species of the genus *Pterocarpus*. Such research endeavors hold promise for unlocking the pharmaceutically valuable compounds inherent in these plants, ultimately contributing to the development of novel drugs with therapeutic potential (Ayéna *et al*., 2022).

## 9. Conclusion

This comprehensive review meticulously scrutinizes a diverse array of species within the *Pterocarpus* genus, painstakingly elucidating the abundant and widespread distribution of pharmaceutically relevant phytochemicals across myriad botanical structures. These encompass verdant foliage, ligneous branches, protective bark, subterranean organs such as roots and rhizomes, as well as reproductive tissues like vibrant flowers and nutrient-rich fruits. The ubiquitous presence of these phytochemical constituents, spanning a vast repertoire of metabolites including polyphenolic flavonoids, intricate terpenoids, intricate alkaloids, and an array of phenolic compounds, is pivotal in conferring the remarkable pharmacological effects that seamlessly align with the time-honored traditional ethnomedicinal applications of *Pterocarpus species* across diverse cultures and geographic regions.

Notably, this exhaustive investigation substantiates these long-standing traditional uses through rigorous scientific evaluation, unveiling the genus's exceptional antimicrobial and antiinflammatory properties. These attributes are further complemented by emerging evidence that elucidates potential applications in combating oxidative stress, a pervasive cellular challenge implicated in numerous pathological conditions. Moreover, intriguing cytotoxic activities against various cancer cell lines have been documented, kindling interest in the development of novel chemotherapeutic agents. Additionally, the moderation of dysregulated glucose metabolism associated with diabetes mellitus has garnered attention, underscoring the genus's versatility in addressing a multitude of health concerns.

In essence, the meticulous comparative analysis of phytochemical composition and pharmacological activities provides invaluable insights into the diverse repertoire of bioactive compounds present in distinct plant sources and their potential medicinal attributes. By rigorously scrutinizing both the intricate chemical constituents and their multifaceted pharmacodynamic effects, researchers can discern promising candidates for pharmaceutical development while concomitantly exploring the inherent synergistic interactions among these natural compounds. This interdisciplinary approach synergistically enhances our understanding of the intricate interplay between phytochemicals and their pharmacological actions, thereby laying a robust groundwork for the judicious exploration and innovation of novel therapeutic agents derived from these botanical sources of immense potential.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## Conflict of interest

The authors declare no conflicts of interest relevant to this article.

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