Journal of Pharmacognosy and Phytochemistry

Available online at www.phytojournal.com

E-ISSN: 2278-4136
P-ISSN: 2349-8234
www.phytojournal.com
JPP 2024; 13(6): 102-111
Received: 29-09-2024
Accepted: 03-11-2024

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Exploring *Tectona grandis*: Phytochemicals, medicinal value, and green innovations: A review article

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DOI: https://doi.org/10.22271/phyto.2024.v13.i6b.15170

Abstract
Teak (*Tectona grandis* Linn.), a deciduous tree in the Lamiaceae family, is renowned for its high-quality, durable timber, sought after worldwide for its resistance to decay, pests, and harsh environmental conditions. Indigenous to tropical regions, Teak is now cultivated broadly across Southeast Asia, Africa, and the Pacific Islands. This species' unique attributes have led to its extensive use in various industries, including traditional medicine, cosmetics, and food. Beyond its timber, Teak also produces bioactive compounds-such as flavonoids, phenolics, and terpenes-known for their antioxidant, antimicrobial, and anti-inflammatory properties. Current research emphasizes the pharmacological potential of extracts from Teak's leaves, bark, and wood in combating conditions such as cancer. Additionally, Teak is valued for its potential in biodiesel production, as well as in paper and pulp industries, with studies delving into the species' phytochemical profile and the processes for extracting these beneficial compounds.

Keywords: Phytochemicals, biological activities, nanotechnology applications, medicinal uses, climate resilience

Introduction

Fig 1: The image shows a close-up view of large, bright green leaves with visible veins, likely from a tropical or subtropical plant

Tectona grandis L.f (TG), commonly known as teak, is a large deciduous tree from the Verbenaceae family, traditionally used in South Asia for medicinal purposes. Various parts of the tree, such as the root, bark, leaves, and wood, are utilized to treat ailments like colds, headaches, wounds, bronchitis, and skin conditions. Teak also exhibits laxative, diuretic, antidiabetic, anti-inflammatory, antioxidant, and lipid-regulating properties. Recent research highlights the broad range of biological activities associated with TG and emphasizes the need for scientific validation of its traditional uses. This review summarizes key phytochemicals, extraction methods, biological activities, and toxicological evaluations of TG. It also explores novel applications, such as natural pigment development, nanoparticle biosynthesis, wastewater treatment, and liver disease therapy. Additionally, studies of teak's molecular responses to environmental stressors and tree-ring isotopic data offer insights into its resilience, providing valuable information for sustainable forest management and climate research.

Taxonomy
Teak (*Tectona grandis* Linn. f.) is one of the most valuable species in the world for producing lumber. It is a member of the Lamiaceae family, which is mostly found in tropical and subtropical regions of the world. The Portuguese term teca, which is a translation of the Greek word tekton, which means carpenter, is where the name Tectona originates. The Latin word grandis means big. There are just three species in the genus Tectona, including *Tectona grandis* linn (Mehta P *et al*., 2022) [49].

Taxonomical Classification

Table 1: Taxonomical classification of *Tectona grandis* (Mehta P *et al*., 2022) [49]

Kingdom	Plantae
Superclass	Angiosperms
Division	Eudicots
Class	Asterids
Order	Lamiales
Family	Lamiaceae
Genus	Tectona
Species	Grandis

Local Names
- **Bengali:** Segun, saigun
- **Burmese:** Kyun
- **English:** Teak wood, Indianoak, teak tree
- **Filipino:** Dalanang, djati
- **French:** Teck
- **German:** tiek, Teak (holz) baum
- **Gujarati:** sagach, saga
- **Hindi:** Saigun, sagwan, sagun
- **Indonesian:** Kulidawa, deleg, jati
- **Italian:** Teck
- **Javanese:** Deleg, kulidawa
- **Malay:** Jati
- **Nepali:** Teak, saguan
- **Sanskrit:** Bardaru, bhumisah, saka, dwardaru, kharchchad
- **Sinhala:** Takku, teaku
- **Spanish:** Teca Swahili - msaji, mtiki
- **Tamil:** Tekku, tekkumaram, tek
- **Thai:** Sak, mai-sak
- **Trade name:** Teak

Common Species
Teak belongs to the family Lamiaceae. There are three species of teak are;
1. *Tectona grandis* (Common teak) is by far the most important, with a wild distribution in Bangladesh, Sri Lanka, India, China, Pakistan.
2. Tectona hamiltoniana (Dahat teak), is a local endemic species confined to Burma, where it is endangered.
3. Tectona Philippines's (Philippine teak) is endemic to the Philippines and is critically endangered according to the IUCN (Palanisamy K *et al*. 2009) [50].

Biophysical Limits
Altitude: 0.0 - 1200 m
Mean annual temperature: 14-36 °C
Mean annual rainfall: (600)1200 - 2500(4000) mm

Botanical Descriptions

Tree morphology
Teak (*Tectona grandis*) is a large deciduous tree native to tropical regions, reaching heights of up to 30-40 meters with a straight, cylindrical bole and a broad, round crown. Teak has a straight and sturdy trunk, often clear of branches for a significant portion of its height. The bark is grayish-brown and can be either smooth or flaky in texture. The leaves are large, ovate, and opposite, typically 30–60 cm long and 20–40 cm wide. They are rough-textured with prominent veins and a hairy underside. During the dry season, teak trees shed their leaves. Teak produces small, white to pale lilac flowers that grow in large, terminal panicles. The flowers are bisexual, with tubular, five-lobed corollas. Flowering usually occurs in the rainy season. The fruit is a drupe, round in shape, and encased in a papery, four-lobed calyx. It contains a hard seed inside, which helps in propagation. Teak is prized for its high-quality, durable wood, which is golden-brown and resistant to termites, decay, and water damage. The wood contains natural oils that give it a shiny, smooth finish (Koffi EN *et al*., 2015) [37].

Flowering phenology
Teak usually flowers six years after planting, but after fifteen years, it begins to blossom profusely. In India the flowering phase commences immediately after the new shoots and leaves flushing stage in late May and continues up to August or September which coincides with the south west monsoon. The local climate has an impact on the blossoming time. In general, The local climate has an impact on the blossoming time. In general, the species flowers between July and October in northern latitudes like India, Myanmar, Thailand, and Laos, and between December and March in southern latitudes like Indonesia and Papua New Guinea. The latitudinal impacts on teak flowering were eloquently established by a series of research conducted in Nigeria. The flowering season runs from February to September in lower latitudes, and from June to October in upper latitudes. There appears to be a connection between teak blossoming and light. Teak flowers are tiny, ranging in size from 6 to 8 mm. They are white, sometimes sporadically reddish pink, and they grow in huge inflorescences or panicles (20 to 90 cm) that start (Palanisamy K *et al*., 2009) [35].

Fruit
A globose, 5 to 20 mm fruit with an accrescent calyx enclosing it, the fruit has an epicarp that is inflated, spongy, and staellate, pubes that are cent, an endocarp that is stony and has four cells, and one or more oblong, exalbuminous seeds. Some of the fruits hang on the tree throughout the hot season, but most mature between November and January and fall off the tree gradually. The fruits range in quantity from 1150 to 2800 per kg and have a yellowish-brown color. When opposed to drier places, fruits in moister regions are heavier g (Mehta P *et al*., 2022) [49].

Materials and Chemicals
The study utilized analytical-grade solvents and reagents, including DPPH, Folin-Ciocalteu's reagent, and various acids and solvents. Extraction was performed on plant leaf powder using methanol and methanol-water mixtures, followed by filtration and concentration. The extracts were stored for further analysis. A large-scale extraction involved soaking 200 g of plant powder in 2000 ml of 90% methanol, followed by defatting with petroleum ether. The defatted methanol extract was fractionated using chloroform, ethyl acetate, and

n-butanol, and the fractions were concentrated and stored for future (Emmanuel NK *et al*., 2016) [11].

Transcriptional and physio-chemical responses of teak leaves triggered by teak defoliator

Because of its economic importance, *Tectona grandis* (L) is a prominent timber species that is farmed in the Indian subcontinent and other nations. The study explores the biochemical and molecular responses of *Tectona grandis* (teak) seedlings to herbivory by defoliators. One-year-old seedlings were exposed to defoliators for nine days, while control plants remained uninfected. The infested plants showed increased levels of soluble proteins, sugars, tannins, lignin, and antioxidant enzymes like catalase and polyphenol oxidase, but decreased peroxidase activity and chlorophyll content. Six herbivory-responsive genes, including ZFP2, ERF-1, Cat1, and Psfp, were upregulated, while the MYB-DNA binding domain gene was downregulated. The study highlights the role of these genes and antioxidant pathways in enhancing teak's defence against insect stress, providing insights for developing herbivory-tolerant plant varieties (Venkatesh YN *et al*., 2024) [1].

Fig 2: The image shows four potted plants labeled A, B, C, and D, each at a different growth stage with varying leaf sizes and health conditions

Physiological and biochemical traits were evaluated in the present study to understand the stress-responsive mechanisms of teak against defoliator herbivory (Fig. 1) (Venkatesh YN *et al*., 2024) [1].

Natural pigments development from teak leaves: utilizing agricultural waste

The research focused on developing a new natural pigment from teak leaves, an agricultural byproduct of the teak industry. Various solvents were used to extract different colors, with ethyl acetate producing the most intense reddish-brown hue. This extract was selected for pigment development using the adsorption method. Aluminium hydroxide ($Al(OH)_3$) was found to be the most effective substrate, producing a purple pigment with the highest intensity due to its ability to adsorb both flavonoids and anthraquinones from the extract. Increasing the $Al(OH)_3$ to extract ratio enhanced the pigment's color intensity, meeting commercial standards. The resulting pigments also demonstrated superior thermal and light stability, suggesting the potential for using teak leaves as a source of natural pigments for cosmetic applications (Charoensit P *et al*., 2021) [2].

Gas exchange response to neighbourhood interferences in teak leaves in a tropical plantation

Neighbourhood interference, a key factor in plant-plant interactions, influences the growth performance of individual plants by affecting gas exchange. In a 21-year-old teak plantation, photosynthesis, transpiration, and stomatal conductance were measured in varying neighbourhood interference conditions using a portable photosynthesis system. Results showed that while diurnal photosynthesis patterns remained unaffected, net photosynthetic rates (Pn) decreased with increasing interference. Weak interference led to significantly higher Pn compared to heavy interference, with a daily maximum Pn ratio of 2.8: 1. Gas exchange parameters like Asat, Qsat, and Vcmax were also higher in weak interference. Changes in light environment had a stronger impact on weak interference individuals, while higher CO2 concentrations affected heavy interference more. This study highlights neighborhood interference as a major factor in intra-specific competition in plantation forests, influencing carbon assimilation and growth, and suggests using interference indices to optimize resource use through proper forest management (Dexiang C *et al*. 2008) [41].

Biosynthesis of silver and gold nanoparticles from teak leaf extract: anticancer and antimicrobial activities

This study explores the eco-friendly synthesis of gold (AuNPs) and silver nanoparticles (AgNPs) using *Tectona grandis* leaf extract, highlighting their potential anticancer and antimicrobial activities. Characterization techniques, including UV-Visible spectroscopy, transmission electron microscopy (TEM), X-ray diffraction (XRD), and Fourier transform infrared spectroscopy (FT-IR), were employed to assess the synthesized NPs. Optimization of parameters such as extract concentration, pH, and incubation time resulted in stable NPs. AgNPs exhibited significant anticancer effects against HepG2 cells (IC50 = 6.17 mg/ml), while AuNPs demonstrated notable antibacterial and antifungal activities against pathogens like Pseudomonas aeruginosa and Aspergillus niger, with inhibition zones ranging from 11 mm to 15.5mm. The findings confirm the medical applications of Teak extract-derived NPs, suggesting their potential to address drug resistance. However, considerations regarding their physical properties and possible toxicity must guide future research (Younis HM *et al*., 2023, Khan *et al*., 2020) [43, 44].

Teak leaf powder for color removal from synthetic and industrial effluents

This study evaluates the effectiveness of untreated teak leaf powder (TLP) in removing color from synthetic and industrial effluents through batch adsorption experiments. The adsorption data were best represented by the Langmuir isotherm, with monolayer capacities of 99.1, 145.2, 188.7, and 207.9 mg methylene blue (MB)/g TLP at temperatures of 293, 303, 313, and 323 K, respectively. Thermodynamic analysis revealed that MB adsorption onto TLP is spontaneous, chemisorptive, and exothermic. Color removal, measured by the absorbance spectrum, showed reductions of 57.41% in color, 45.95% in chemical oxygen demand (COD), and 49.46% in total dissolved solids (TDS) for a 10% diluted effluent. The monolayer capacity for TDS was determined to be 219 mg/g. These results indicate that untreated teak leaf powder is a promising adsorbent for effectively treating colored wastewater (Ponnusami V *et al*., 2009) [45].

Teak leaf extract alleviates hepatic fibrosis via TGF-β/smad pathway modulation and mmp3/timp1 ratio regulation

Tectona grandis L.f. (syn. Jatus grandis (L.f.) Kuntze Revis), belonging to the Lamiaceae family and commonly known as Teak, is well-regarded in Ayurveda for its therapeutic properties against inflammation, liver disorders, diabetes, and other ailments. The leaves are a rich source of a non-toxic edible food colorant. Given the global health challenge of hepatic injury progression to cirrhosis and cancer, there is a pressing need for effective, FDA-approved anti-fibrotic treatments. This study aimed to evaluate the ameliorative effects of *Tectona grandis* leaves in early liver fibrosis. The findings revealed that the methanol extract of *Tectona grandis* leaves exhibited protective effects against carbon tetrachloride (CCl4)-induced hepatic damage in mice, in a dose- and time-dependent manner. The extract was shown to regulate the TGF-β/Smad signaling pathway, contributing to its anti-fibrotic activity. Key extracellular matrix markers, including αSMA, Col 1, PDGF, TIMP1, and MMP3, were significantly modulated following treatment with *Tectona grandis*. Overall, the results suggest that *Tectona grandis* leaves may offer a promising therapeutic approach for mitigating liver fibrosis, comparable to the effects observed with silymarin (Tariq S *et al*., 2021) [46].

Thailand teak tree-ring oxygen isotope chronology in North-western

This study developed a stable oxygen isotope (δ18O) chronology from tree-ring alpha cellulose in archaeological teak wood from Mae Hong Son, Thailand, spanning 283 years during the late Holocene (AD 14–296). The δ18O values, ranging from 21.15‰ to 26.31‰, serve as a proxy for past monsoon precipitation patterns. The study found significant correlations between the teak δ18O record and regional hydroclimate variability, highlighting influences from climate phenomena like the Pacific Decadal Oscillation (PDO) and El Niño-Southern Oscillation (ENSO). This research offers valuable insights into the relationship between past climate conditions and human activity in the region, using tree-ring records from ancient teak coffins (Preechamart S *et al*., 2022, Pumijumnong *et al*., 2020) [47, 48].

Multifunctional use of heterogeneous catalyst from littered teak leaves for biodiesel and chemical production

Calcined *Tectona grandis* leaves were proposed as an eco-friendly, renewable, and low-cost heterogeneous base catalyst for chemical transformations. The catalyst, characterized by FTIR, XRD, XPS, SEM, EDX, TEM, TGA, BET, and Hammett indicator tests, features basic surface sites from alkali and alkaline earth metals. It demonstrated high efficiency in biodiesel production, achieving 100% FAME conversion with 2.5 wt% catalyst under optimized conditions, confirmed by 1^{1}1H and 13^{13}13C NMR. The catalyst also proved effective and recyclable in the Knoevenagel condensation reaction for synthesizing benzylidenemalononitrile derivatives from aryl aldehydes. As a "green catalyst" derived from waste biomass without added chemicals, it offers an environmentally benign alternative to industrial base catalysts for biodiesel production and Knoevenagel reactions (Gohain M *et al*., 2020) [4].

Synthesis of ZnO nanoparticles using leaf extract of teak

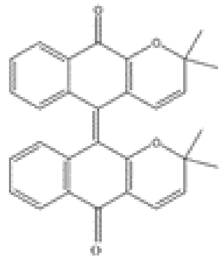
This study explores the antibacterial, anti-arthritic, antioxidant, and *in vitro* cytotoxic activities of green-synthesized Zinc Oxide Nanoparticles (ZnO NPs) using an aqueous leaf extract of *Tectona grandis*. Zinc nitrate served as the precursor and the leaf extract as the reducing agent. The ZnO NPs were characterized by powder X-ray diffraction (PXRD), which determined their crystalline size using the Scherrer formula. FTIR analysis confirmed functional groups in both the leaf extract and ZnO NPs. UV absorption showed a peak at 360 nm with a calculated energy band gap of 3.4 eV. Dynamic Light Scattering (DLS) analysis indicated good stability and particle size, while FE-SEM revealed crystalline size, shape, and surface morphology. The green-synthesized ZnO NPs demonstrated significant antibacterial activity against both Gram-positive and Gram-negative bacteria, strong DPPH free radical scavenging, and high protein denaturation (90.46%) and proteinase inhibitory activity (87.68%) at 200 µg/ml. Additionally, ZnO NPs exhibited anticancer effects by reducing cancer cell size in osteoblast MC3t3-E1 cell line (Senthilkumar N *et al*., 2017) [10].

Phytochemical Studies

Different chemical components that were separated from various plant T sections. (1) have been given in table-I and structures of some constituents are given below;

Table 2: Phytoconstituents of *T. grandis* (Gupta PK *et al*., 2004, Aquinaldo AM *et al*., 1993) [31, 39].

Sl. No.	Plant part	Chemical constituents isolated
1.	Wood	Resin, silica, calcium phosphate, ammonium phosphate, magnesium phosphate, Anthraquinone-2carboxylic acid, anthraquinone-2-carboxaldehyde Triterpenic and hemiterpenic compound, 9,10-dimethoxy-2-methyl-1,4-anthraquinone,5-hydroxy-2-methyl-9,10-anthraquinone, 1-hydroxy-5-methoxy-2-methyl-9,10-anthraquinone 1,5-dihydroxy-2-methyl-9,10-anthraquinone, tecomaquinoneI(I), tectoquinone, dehydro-α-lapachone, lapachol, 5-hydroxy-lapachol, methlyquinizarin, squalene, Dehydro-α-isodunnione, Lignins.
2.	Root	tectoionols-A (V), monoterpene, apocarotenoids, Protein (7.1%), crude fiber (22.3%), calcium (3%), phosphorous (0.46%) Steroidal compound squalene, polyisoprene-α-tolylmethyl ether and betulinic acid, anthraquinonenapthaquinone pigment, tectograndone.
3.	Leaves	Lapachol, Tectol (II), dehydrotectol, tectoquinone, β-lapachone, dehydro-α-lapachone, β-sitosterol, new diterpene, tectograndinol (III) Non-structural carbohydrates, 1-hydroxy-2-methyl anthraquinone, pachybasin, obtusifolina, betulinic acid.
4.	Seed	Seed oil contain fatty acids as caprylic (1.45%), capric (0.76%), lauric acid (6.77%), myristic acid (2.86%), palmitic acid (12.12%), stearic acid (9.52%), oleic acid (23.33%) and linoleic acid (43.22%), Xanthene.
5.	Bark	Tannin (7.14%), 5-hydroxy-1, 4-napthalenedione (VI) (juglone), Obtusifolina (VII), Desidro-α-lapachona (VIII).



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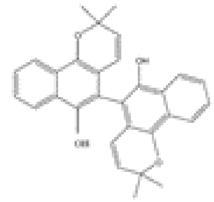

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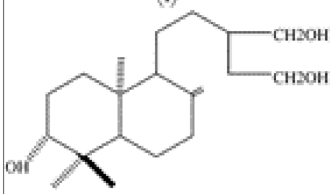

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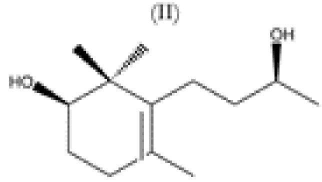

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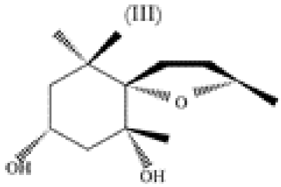

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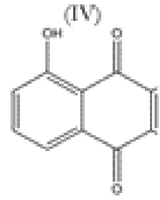

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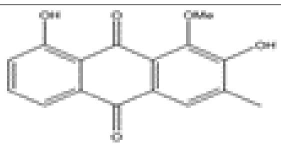

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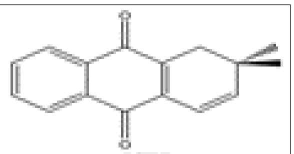

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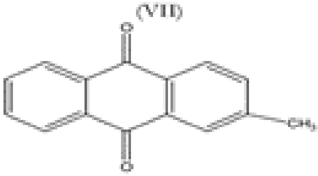

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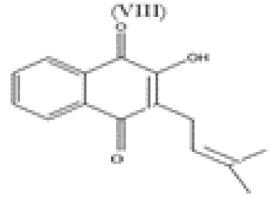


(X)

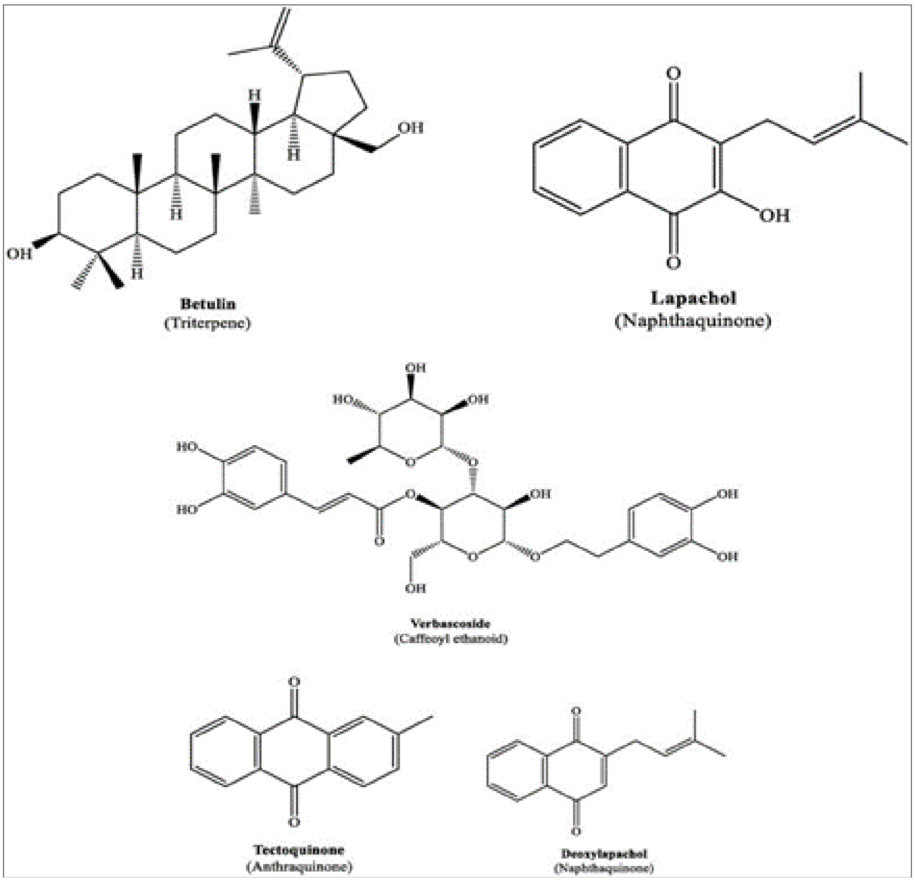
Preliminary phytochemical screening

Thin layer and paper chromatography

Using several eluting systems that cover non-, medium-, and high-polar components, phytochemical screening was carried out for the active fractions in order to determine the presence of secondary metabolites using TLC analyses (Pre-coated aluminum silica gel plates, GF254, Merck). The solvent systems are as follows: (CHCl3: MeOH: 1:1; n-BuOH: MeOH: H2O, 4:1:0.5); (CHCl3: MeOH: EtOAc: MeOH, 2:2:1); (CHCl3: MeOH, 9:1 and 8.5:1.5). The following spraying reagents were used in order to develop the spots: 1% ferric chloride (Tannins), 2% aluminium chloride in ethanol (Flavonoids), 40% sulphuric acid/methanol (Saponins), and Dragendorff reagent (Alkaloids). Also, one dimensional paper chromatography was performed on Whatmann No. 1 (57 x 46 cm) with 15% AcOH/H2O and BAW solvent systems (n-BuOH: AcOH: H2O, 4:1:5 organic layer). After drying the change of spots colour on the chromatograms was detected by exposing to ammonia vapor or spraying with 1% methanol AlCl3 or FeCl3 (Qui H *et al*., 2019, Sultana S *et al*., 2012) [7, 16].

Phytochemical tests: Conventional standard protocols for detecting the presence of different chemical constituents in the plant extracts were employed. The tests for the secondary metabolites *viz*. Preliminary phytochemical screening was used to determine the presence of alkaloids, tannins, sterols, saponins, glycosides, sterols/terpenes, reducing sugars, non-reducing sugars, flavonoids, and phenols in the methanolic extracts of *T. grandis* leaves.

Tectona grandis (TG) phytoconstituents are identified and quantified using a variety of analytical techniques, including gas chromatography-mass spectrometry (GC-MS), high-performance thin-layer chromatography (HPTLC), and high-performance liquid chromatography (HPLC). Early research on a variety of plant parts, including the bark, wood, leaves, flowers, and fruits, has identified important substances such glycosides, alkaloids, phenolics, and flavonoids. According to ICH recommendations, these secondary metabolites have been quantified using a variety of techniques, with prior investigations documenting the chemical structures of the primary constituents. Below are the molecular structures of a few significant TG components, (Kamath KK *et al*., 2024, Vyas P *et al*., 2019, Singh PA *et al*., 2016, Srivastava S *et al*, 2008 [8, 12, 29].



Toxicological Studies

Acute toxicity studies assess the potential for a substance to cause death or serious harm when administered in a single dose or over a few doses. For *Tectona grandis* (TG), various parts of the plant were tested at doses ranging from 1000 to 5000 mg/kg body weight using water, methanol, and ethanol as solvents. The studies found no signs of toxicity even at the highest dose of 5000 mg/kg. Most studies, however, used a maximum dose of 2000 mg/kg. The research indicates that TG extracts have a relatively high safety margin (Francisco AM *et al*., 2010) [38].

Teak allergy

Plants, including tropical hardwoods like teak, are significant causes of contact dermatitis. Teak, in particular, can lead to both irritant and allergic contact dermatitis due to its potent sensitizers. Identified allergens in teak include polyphenols, naphthoquinones, lapachol, and deoxylapachol. Deoxylapachol is a stronger sensitizer than lapachol (Rao R. *et al*., 2010) [56].

Patent literature of *Tectona Grandis* leaf

Patents related to *Tectona grandis* (TG) cover various aspects such as cultivation, harvesting, drying, extraction, standardization, and formulation methods. Patent literature was reviewed using keyword searches in the Espacenet Patent Search database. Patents and applications mentioning TG or teak wood with pharmaceutical uses were selected and analyzed for their content and descriptions (Asdaq S *et al*., 2021) [55].

Pharmacological studies pharmacological activities

The global use of herbal products has grown significantly in recent years, as they have traditionally served as a vital source for drug development. However, understanding the complex molecular interactions and bioactivity mechanisms of herbal extracts and their constituents remains challenging for researchers. *Tectona grandis* Linn. (TG) is known for its diverse pharmacological activities. This article offers a summary of these activities, highlighting TG's potential therapeutic benefits.

Antimicrobial activity

The antimicrobial activity of *Tectona grandis* was assessed using the disc diffusion method. The pure variety showed varying levels of inhibition against Staphylococcus aureus, Salmonella typhi, and Bacillus cereus, with no effect on Escherichia coli. The hybrid variety exhibited stronger antimicrobial activity, particularly against Staphylococcus aureus. The enhanced activity in the hybrid could be due to genetic modifications that increase active compound concentrations. Key bioactive compounds in *Tectona grandis* leaf extracts, such as tectoleafquinone and tectoquinone, contribute to its antimicrobial and antioxidant effects. The resistance of Escherichia coli is attributed to its complex cell wall structure (Neha K *et al*., 2013, Sen S *et al*., 2012, Choudary GP *et al*., 2010) [14, 19, 25].

Anti-anaemic effect

The extract of *Tectona grandis* leaves was tested on an anaemic rat model induced by phenyl hydrazine. Oral administration of the extract at a dose of 1 g/kg/day resulted in increased haemoglobin levels, red blood cell count, haematocrit, and reticulocyte rates. Additionally, the extract improved the osmotic resistance of red blood cells, indicating a higher presence of young red blood cells. These findings partially support the traditional use of *T. grandis* in treating anaemias (Mishra A *et al*., 2019) [6].

Wound healing activity

The study evaluated the wound healing effects of a hydrochloric extract of *Tectona grandis* on rats with experimentally induced wounds, comparing its efficacy to Aloe vera. Four wound models were tested: excision, incision, burn, and dead space wounds. The *T. grandis* leaf extract significantly reduced the period of epithelialization and wound contraction by 50% in excision and burn wound models and increased breaking strength in the incision wound model. In the dead space wound model, oral administration of the extract enhanced breaking strength, dry weight, and hydroxyproline content of granulation tissue. The results suggest that both topical (5% and 10% gel) and oral (250 and 500 mg/kg) application of *T. grandis* extract have effective wound healing properties (Varma SKB *et al*., 2013, Sharma Y *et al*., 2013, Venkatanarayana D *et al*., 2010), Majumdar M *et al*., 2007) [13, 15, 26, 30].

Antioxidant activity

The study examined the *in-vitro* antioxidant activity of an ethanolic extract of *Tectona grandis* (TG) using DPPH, FRAP, and H_2O_2 scavenging assays. The extract demonstrated IC50 values of 37.5 µg/ml for DPPH and 32.0 µg/ml for H2O2 scavenging, with a 50% reduction in ferricyanide complex at 190 µg/ml. These results, comparable to ascorbic acid, suggest that the antioxidant properties of TG may be attributed to tannins and saponins, indicating its potential efficacy against free radical-mediated diseases (Suryani V *et al*., 2020), (Murukan G *et al*., 2018) [3, 9, 32].

Antifungal activity

A methanolic crude extract of *Tectona grandis* was tested at different concentrations (1000 to 5000 µg/ml) for its antifungal activity. The extract demonstrated significant inhibition of fungal growth, with 90.00% inhibition against Alternaria cajani and 86.84% against Helminthosporium. The antifungal activity increased with higher concentrations of the extract, showing maximal efficacy at the highest concentration tested Bhat IH *et al*., 2010, Gupta VK *et al*., 2010, Verma N *et al*., 2008, Shalini *et al*., 2009) [21, 24, 28, 36].

Antiviral activity

The extract of *Tectona grandis* demonstrated a high antiviral activity, showing approximately 85% inhibition of the Tomato Spotted Virus. Additionally, *T. grandis*, in combination with Lawsonia inermis, Butea monosperma, and Carica papaya, exhibited antifertility effects, suggesting its potential use as a birth control agent (Pal DC *et al*., 1998) [38].

Anti-inflammatory activity

The ethanolic and aqueous extracts of *Tectona grandis* stem bark demonstrated significant dose-dependent analgesic and anti-inflammatory activities in rats. Both extracts, particularly at a dose of 500 mg/kg, showed rapid and sustained effects, with the aqueous extract exhibiting stronger anti-inflammatory potential than indomethacin and paracetamol. The aqueous extract also significantly reduced carrageenan-induced paw oedema, suggesting its effectiveness in acute inflammatory conditions. Previous studies support these findings, showing consistent anti-inflammatory activity in both *in vivo* and *in vitro* models using various parts of the plant (Neha K *et al*., 2013) [35].

Antibacterial activity: Preliminary studies on the antibacterial activity of *Tectona grandis* extracts showed that chloroform extract from the leaves was the most effective, particularly against Staphylococcus aureus and Klebsiella pneumoniae. Methanol extracts from leaves and ethyl acetate extracts from wood also displayed moderate activity against both Gram-positive and Gram-negative bacteria. The antibacterial compound 5-hydroxy-1, 4-naphthalenedione (Juglone) was identified as a key active ingredient. The effectiveness of *Tectona grandis* extracts was comparable to conventional antibacterial treatments, such as Silver Sulphadiazine (SSD). Further studies confirmed the synergistic potential of these extracts with tetracycline, enhancing their activity against multi-drug-resistant bacteria. Additionally, teak extracts exhibited strong activity against pathogens associated with burn injuries and demonstrated effectiveness against Listeria monocytogenes and methicillin-resistant Staphylococcus aureus (MRSA) (Prasannabalaji N *et al*., 2012, (Krishna MS *et al*., 2010, Purushotham KG *et al*., 2010, Omer EU *et al*., 2006) [17, 20, 23, 33].

Anti-termite Activity

In a study on *Tectona grandis* (Teak) bark, subterranean termites (Reticulitermes speratus) were exposed to chloroform-treated paper discs to assess the bark's termite resistance. The test involved maintaining termites in controlled conditions and measuring their survival and the weight loss of treated discs after 10 days. While deoxylapachol, a compound found in teak bark, was detected, it showed minimal effect on termite deterrence, indicating that the bark's overall anti-termite efficacy is not solely due to this compound (Bhargava S *et al*., 2012) [18].

Antipyretic Activity

The antipyretic (fever-reducing) effects of *Tectona grandis* seeds were tested in albino rats using Brewer's yeast to induce fever. The study demonstrated that seed extracts significantly reduced fever in a dose-dependent manner, with effects comparable to the standard drug, paracetamol. The results suggest that the antipyretic action might involve interference with prostaglandin production and other inflammatory mediators (Kiritar KR *et al*., 2000) [34].

Antidiabetic activity

Tectona grandis methanol extract has demonstrated promising antioxidant and antidiabetic effects in rat models of alloxan-induced diabetes. To determine the active principles, more research is now being conducted. A single chemical or a combination of compounds may be the active principles (Goswami DV *et al*., 2009) [27].

Hair growth promoting activity

Leaf extracts of *T. grandis* may be present in over-the-counter medications or cosmetics intended to treat hair loss. This is demonstrated by their S5AR inhibitory activity, effect on HFDPCs, antitestosterone activity as well as antiinflammatory activity through 1L-1β secretion inhibition (Fachrunniza *et al*., 2020) [54].

Insecticidal activity

Ethanolic and methanolic extracts from three varieties of teak leaves were tested against the 3rd instar larvae of the diamondback moth (DBM). The extracts showed high insecticidal effectiveness, with 65.6–82.6% larval mortality at 24 hours and over 96.3% mortality at 48 hours when used at a 10% concentration. The lethal concentration (LC50) values ranged from 7.2–8.8% at 24 hours and 4.9–6.4% at 48 hours, with no significant differences in efficacy among the three teak varieties (Pumnuan J *et al*., 2021) [53].

Tectona grandis adsorbed cadmium (II) ions from an aqueous solution

Batch adsorption studies using *Tectona grandis* L.f leaf powder as a biosorbent were conducted to remove cadmium (II) from aqueous solutions. Experiments varied conditions such as time, temperature, Cd (II) concentration, pH, adsorbent dosage, and particle size. Results showed that 1 g of *Tectona grandis* L.f removed 86.73% of Cd (II) from a 50 mL solution within 30 minutes. The adsorption data fit both Langmuir and Freundlich isotherm models, with a monolayer sorption capacity of 29.94 mg. Optimal adsorption occurred at pH 5.5, and the kinetics followed a pseudo-second-order model. Adsorption was slightly affected by temperatures between 30 °C and 50 °C. SEM analysis revealed agglomerates, and FTIR showed a negative shift in wave numbers (Rao KS *et al*., 2010) [22].

Synergistic invitro antibacterial activity

The frontal leaves of *Tectona grandis* (Verbinaceae) are traditionally used to treat infections. This study aimed to develop a cost-effective antimicrobial agent against multi-drug-resistant organisms by combining Tetracycline with a methanolic extract of *Tectona grandis*. The Minimum Inhibition Concentration (MIC) of the methanolic extract with Tetracycline ranged from 62.5 µg/ml to 2000 µg/ml against nine different Gram-positive and Gram-negative bacteria. The combination showed maximum synergistic activity against Salmonella typhimurium (MTCC 98) and Klebsiella pneumonia (MTCC 432), and the least activity against Pichia pastoris (MTCC 34) and Escherichia coli (MTCC 729). No synergistic effect was observed for Citrobacter freundii (MTCC 1658) (Purushotham KG *et al*., 2010) [52].

Wound healing activity of teak leaf extract on rats

Healthy albino rats (150-200 g) were used to evaluate the wound healing effects of *Tectona grandis* (TG) leaf extract in excision and incision wound models. The rats were divided into four groups: control (simple ointment), 5% TG leaf extract ointment, 10% TG leaf extract ointment, and standard (soframycin ointment). In the excision model, wound contraction was measured, while tensile strength was assessed in the incision model. Statistical analysis showed that the 5% TG ointment significantly reduced wound area from the 8th day ($p < 0.01$), and the 10% TG ointment and soframycin significantly reduced wound area from the 4th day ($p < 0.001$). In the incision model, the 5% TG ointment significantly increased tensile strength ($p < 0.05$), and the 10% TG ointment and soframycin showed a very significant increase ($p < 0.001$). Overall, TG leaf extract demonstrated significant wound healing activity (Varma S *et al*., 2013) [1].

Nitric Oxide Scavenging Activity

The hexane extract of *Tectona grandis* was tested for its ability to regulate nitric oxide (NO) levels *in vitro* using sodium nitroprusside as an NO donor. The extract effectively scavenged NO, demonstrating significant antioxidant activity (Jagetia GC *et al*., 2004) [51].

Miscellaneous

Myanmar timber extract of *T. grandis* was showing potent leishmanicidal activity. The chemical constituent of the plant was found quinone derivatives.

Conclusion

This review consolidates current knowledge on the phytochemical and pharmacological properties of *Tectona grandis* L.f, emphasizing its potential as a source of bioactive compounds for various therapeutic applications. The compilation of data from numerous studies underscores the plant's diverse biological activities, including antioxidant, antimicrobial, antidiabetic, anti-inflammatory, wound healing, and cytotoxic effects. The review highlights the importance of continued research to further explore the therapeutic potential of *Tectona grandis*, optimize its use in medicine, and fill gaps in existing knowledge. Given its traditional uses and documented bioactivities, *Tectona grandis* holds promise as a valuable plant in the development of novel, natural therapeutic agents.

Acknowledgement

We wish to thanks to our beloved guide Sr. Anna C.K, M. Pharm, Assistant Professor, Dept of Pharmacognosy, Caritas college of pharmacy, Kottayam, who is like a heart of this valuable work for her kind patience, suggestions, clarifications, valuable guidance and inexpressible moral support of encouragement.

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