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REVIEW ARTICLE

Phytochemistry of *Chukrasia tabularis* A. Juss: A reservoir of bioactive compounds with ecological and economic importance

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Abstract

Chukrasia tabularis A. Juss, a lesser-known species from the Meliaceae family, is gaining attention for its rich phyto-pharmaceutical potential conferred by its bioactive compounds, namely, limonoids, flavonoids, tannins and essential oils. Widely used in traditional medicine systems like Ayurveda, Siddha and Chinese medicine, because this plant possesses numerous therapeutic properties like that of antimicrobial, anti-inflammatory, antimalarial and cytotoxic. It is historically used and its phytochemical composition and pharmacological properties have not been explored fairly in science. Studies in recent years have demonstrated that *C. tabularis* bark, leaves, seeds and wood are rich in bioactivity especially in the fight against microbial infections and cancer. The plant extracts were found to have antimicrobial activity against a wide range of bacterial and fungal strains; hence the plant has potential for natural antimicrobial agent. In addition, its limonoid rich extracts are cytotoxic properties and could be used as anticancer agents targeting different cancer cell lines and overcoming multidrug resistance (MDR). In addition, these therapeutic benefits may include chronic inflammatory and oxidative stress-related diseases due to the plant's anti-inflammatory and antioxidant properties. *C. tabularis* has a wide range of medicinal uses, but it is also important in agriculture and forestry due to its use as a biopesticide, soil enhancer and natural dye supplier. It also has high quality timber and serves the country's ecological and economic importance. Nevertheless, more complex toxicity assessments and clinical trials are needed to verify them safety and therapeutic potential. This review highlights the importance of further research on combining *C. tabularis* into current pharmaceutical and sustainable mechanisms and the in-depth studies on *C. tabularis* to support its integration into modern medicine, pharmaceuticals and sustainable industries.

Keywords: *Chukrasia tabularis*; bioactive compounds; medicinal properties; phytochemistry; sustainability

Introduction

However, as the world finally emerges from the pandemic, traditional folk medicine and particularly plant-based medicines as remedies have surged back in use across the globe. Key trend in modern health care is growing interest in Indian traditional medicine which emphasises the role of plant as a potential therapeutic agent. Secondary metabolites of plants also aid to prevent degenerative disease via scavenging of free radicals and inhibition of oxidative stress which results in chronic conditions (1). It is believed that tree families are rich in different activities bio compounds which have medicinal properties thus making them important in the treatment of many diseases. Much research, however, has been focused on one family-Meliaceae included more than 48 genera and more than 700 species mostly occurring in tropical and subtropical regions having various auxiliary phytochemistry and various bioactive compounds. In addition, these trees are used in different industries such as medicine, cosmetics, agriculture and even in producing insecticides (2). It is of lesser-known species in the family Meliaceae and has got remarkable medicinal properties; such species is *Chukrasia tabularis* A. Juss. It is a tropical and subtropical Asia (India, Bangladesh, mainland China and Southeast Asia) fast growing, deciduous tree (3). In traditional medicinal systems such as Ayurveda, Siddha and Chinese medicine, *C. tabularis* is renounced for its wealth of phytochemical content. The utilizable parts *C. tabularis* A. Juss possessing bioactive compounds are represented in Fig. 1. Among them are limonoids, flavonoids, tannins and essential oils. Therapeutic effects are endorsed to these bioactive compounds which display antioxidant, antimicrobial, anti-inflammatory, antimalarial and cytotoxic activities (4). Although it is extensively used in traditional medicine, its bioactive compounds and the pharmacological potential have neither been studied scientifically. The dual medicinal properties of *C. tabularis* have been covered by

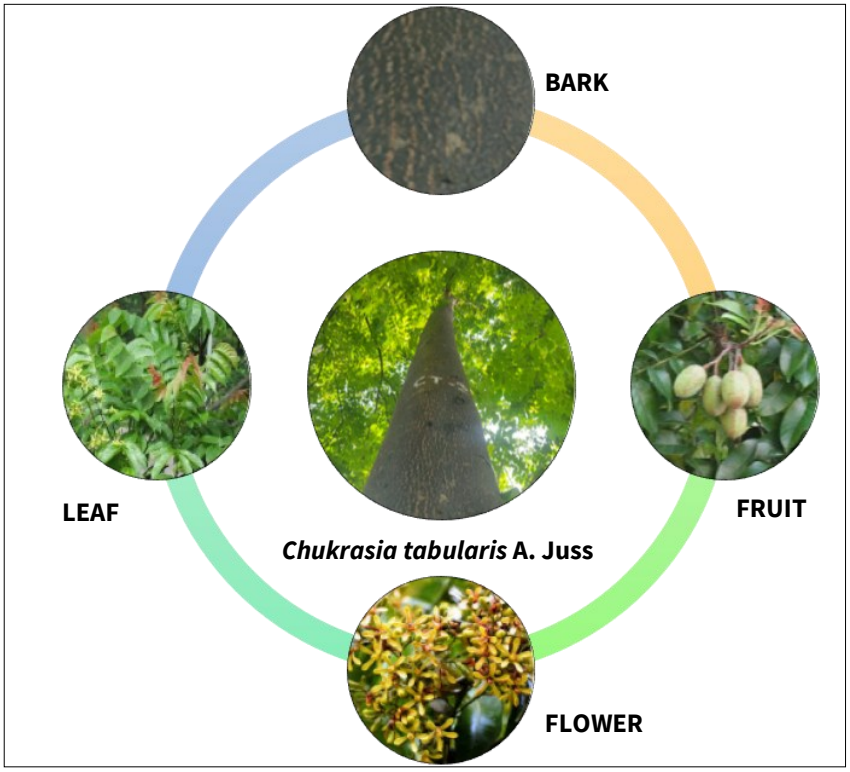

Fig. 1. Utilizable parts *Chukrasia tabularis* A. Juss possessing bioactive compounds.

recent studies, which claim that its leaves can be applied to treat fever, skin diseases, respiratory problems and gut disorders. The bark and leaves of this plant have been shown to have anti-inflammatory, hepatoprotective and wound healing properties. Some of the bioactive constituents identified by phytochemical screenings include limonoids (4), flavonoids and phenolic compounds (5), respectively. Tannins and alkaloids (6), terpenoids and steroids and essential oils that give it antioxidant, antimicrobial and anti-inflammatory activities (6, 7). The pharmacological properties of and the potent antioxidant effects of *C. tabularis* of extracts in (7) made them candidates to protect against oxidative stress related diseases because of their antioxidant properties. Indeed, as with other antimicrobial products from plants, limonoids extracted from the bark in the form inhibited pro-inflammatory cytokines (4). Its essential oils from leaves are effective against bacterial as well as fungal pathogens (6). Additionally, *C. tabularis* has been shown potential for cancer treatment due to the cytotoxic effects of extracts from this *C. tabularis* on different cancer cell lines (8, 9). It has been widely used to exploit its antimalarial properties for traditional use to treat fevers and infection (8). Although its great potential, there is a lack of comprehensive toxicity studies, clinical trials and pharmacological research necessary to approve its therapeutic applications. In addition to its economic importance with its high-quality timber, use of natural dyes, use in eco-friendly agriculture and medicine (10). It is also known to be used in agroforestry (shade tree; soil fertility contribution; biopesticide). Recent advances in phytochemical research have begun to uncover the full potential of *C. tabularis* in drug development, highlighting the importance of integrating traditional knowledge with modern scientific approaches to harness its full medicinal, ecological and economic benefits.

Chemical diversity and therapeutic potential of *C. tabularis*

The diversified chemical nature of *C. tabularis* represents different chemical constituents in various forms where it all exhibits some therapeutic properties which marks its importance in medicinal field. The major constituents contribute significantly to its curative properties for various ailments. The significant source of structurally diverse limonoids, which are modified triterpenes distinguished by a 4,4,8-trimethyl, 17-furanyl steroid framework in chukrasia was depicted (11). The differences in ring structures and the positioning of functional groups within this core framework enhance the plant's structural diversity, attracting considerable scientific attention. Limonoids belong to the tetranortriterpenoid class and are categorized based on the oxidation pattern of their four rings (labeled A, B, C and D within the intact triterpene nucleus). The first limonoids identified in the wood and seeds of *C. tabularis* were ester derivatives of phragmalin (2,3,30-trihydroxy,1,8,9-orthoacetate), which feature a tricyclo ($3.3.1^{2},^{10},^{11},^{4}$) decane ring system (12). The Chukrasia genus is distinguished by its characteristic phragmalin-type limonoids, which include various subtypes such as normal phragmalins and their orthoesters (13). Other notable variants were identified and reported (13-15) which includes 13/14/18-cyclopropanyl phragmalin-type limonoids, C (15)-acyl 16-norphragmalins, C (15)-acyl phragmalins (16) and some others were mentioned as 16-norphragmalins, 19-dinorphragmalins and 16,19-dinorphragmalins (17-19). Various types of bioactive compounds are present in different regions of Chukrasia. As mentioned, the seeds are rich in meliacins, including 3,30-diisobutyrates and 3-isobutyrate-30-propionates of phragmalin and 12-acetoxyphragmalin. Leaves and bark contain tabularin (5,7-dihydroxy-6,2',4',5'-tetramethoxyflavone) and tannic acid. Leaves also have quercetin, quercetin-3-galactoside and additional tannic acid. Roots possess cedrelone, a triterpenoid. Wood contains various chukrasins and bussein homologues. Accordingly, these constituents are classified into primary, secondary and tertiary categories (Table 1) based on their functions. The medicinal field has significantly expanded over the past decades to address critical challenges. Its remarkable advancements in technology have gained substantial importance. Various extraction methods are being developed to isolate

Table 1. Classification of chemical constituents in different parts of *Chukrasia tabularis*

Different parts of Chukrasia	Primary constituents	Secondary constituents	Tertiary constituents
Seed	Phragmalin Derivatives Meliacins (Limonoid Esters)	3,30-Diisobutyrates of Phragmalin 3-Isobutyrates-30-Propionates of Phragmalin 12-Acetoxyphragmalin Chukrasin A, B, C, D and E	Tabularisin A, B, C, D, E, G, H, I
Root	Tabularin Cedrelone Sitosterol	Tabulalide A, B, C, D, E	-
Bark	Scopoletin Tannic acid Tabularin Melianone	7-Dimethoxycoumarin Tabulalide A, B, C, D, E	Chuktabularin A, B, C, D
Leaves	Quercetin Tannic acid Tabularin	Chuktabrin A, B	Tabularisin A, B, C, E, G, H, I (24R)-28,29 Dinor cycloartane 3 ,24,25-triol
Twigs	Tabularin Melianone Tabularin	Chuktabrin A, B	Tabularisin A, B, C, E, G, H, I (24R)-28,29 Dinor cycloartane 3 ,24,25-triol
Wood	Chukrasin A, B, C, D, E	Bussein Homologue	-

Sourced from Ref. (8-10, 26, 45).

metabolites (13, 16). Notably, sitosterol, scopoletin, 6,7-dimethoxycoumarin and melianone have been isolated from the bark's petroleum and alcoholic extracts, respectively (18). Tabularin has also been synthesized through oxidative cyclization of chalcone, followed by deprotection using boron trichloride under mild conditions (15) (16). Recent studies have further expanded the phytochemical profile of *C. tabularis*. For instance, six phragmalin limonoids, including tabulalin and five tabulalides (A-E), were isolated from the root bark collected in Xiantan, China. Fig. 2 represents the chemical structure of important bioactive compounds. These compounds were obtained as white amorphous powders using droplet counter current chromatography and reversed-phase HPLC techniques (16, 19).

Phytochemical profile of *C. tabularis*

The phytochemical profile has various pharmacological aspects in diverse fields with which it is considered as the surge in recent days. Though Chukrasia is one among the meliaceae family its phytochemical profile is reviewed as the valuable resource in traditional and modern medicine. Fig. 3 depicts the percentage distribution of phytochemicals in *C. tabularis.* Phenolic compounds are known for their antioxidant properties, which contribute to the plant's ability to neutralize free radicals. In *C. tabularis*, the total phenolic content is significant, with a measurement of 17.2 mg GAE/g, indicating its potential as a natural antioxidant source (20). Flavonoids are a group of polyphenolic compounds with various biological activities,

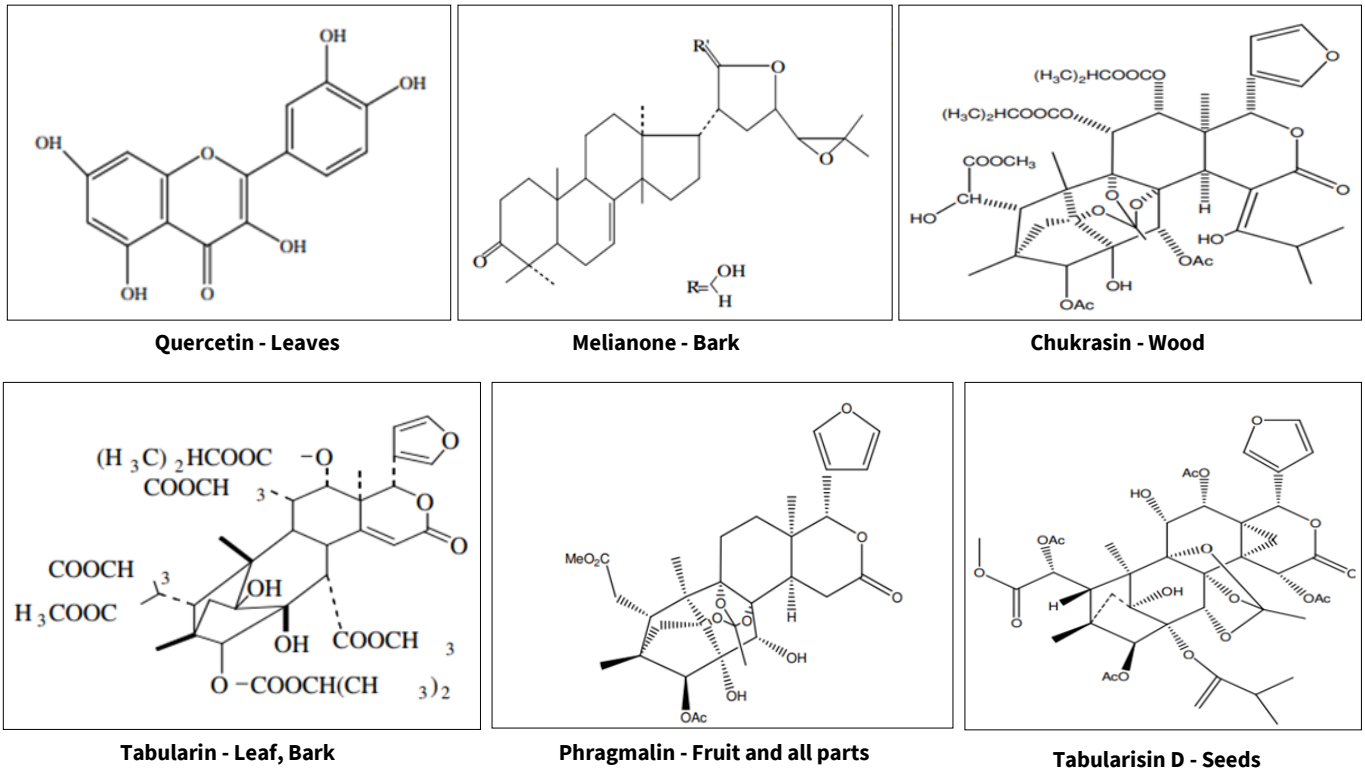

Fig. 2. Chemical structure of *Chukrasia tabularis* A. Juss bioactive constituents. Sourced from Ref. (8, 9, 25, 46).

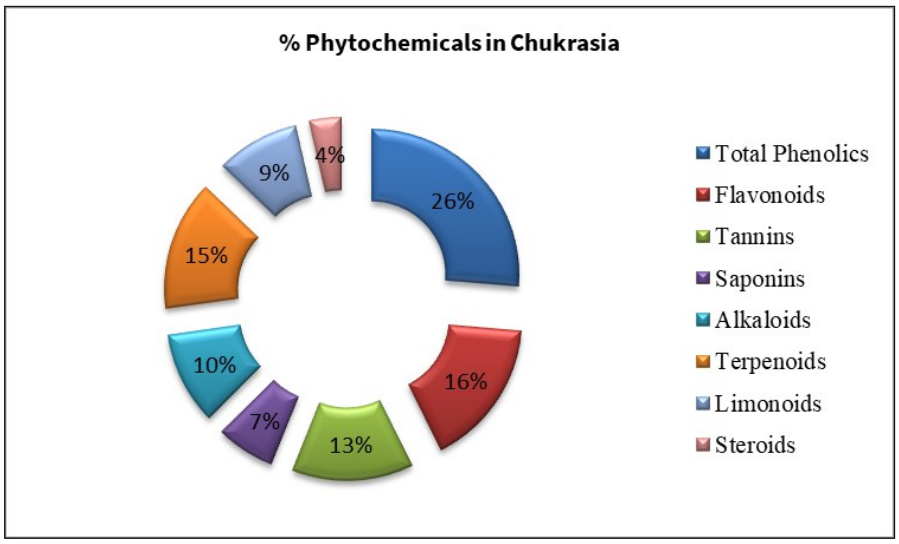

Fig. 3. Distribution of phytochemicals in *Chukrasia tabularis.* Sourced from Ref. (11, 15).

including antioxidant and anti-inflammatory effects. It contains a notable number of flavonoids, with a total flavonoid content of 3.82 QE/g, which supports its use in traditional medicine for its health benefits (20). Tannins are polyphenolic compounds that can bind to proteins and other organic compounds, often contributing to the astringency of plants. It generally helps in the plant's defence mechanisms and its potential therapeutic properties. Glycosides known for their potential health benefits, including cholesterol lowering and immune boosting effects and that have foaming characteristics are saponins. There are no papers provided regarding saponins presence in *C. tabularis*, but saponins are usually present in many medicinal plants. Properties of bioactive constituents of *C. tabularis* is mentioned in Table 2. Nitrogen containing compounds that sometimes have a major pharmacological effect are called alkaloids. There are exceptions and these are associated with the medicinal properties of the plant. A large class of naturally occurring organic chemicals found in terpenes are terpenoids. Aromatic properties and potential therapeutic effects are known to them. Among the terpenoids present on *C. tabularis* are triterpenoids that have been isolated, characterised and studied as to their bioactive properties. Triterpenoids are chemicals with a very wide range of biological activities including anti-inflammatory and anticancer activities. Limonoids rich *C. tabularis*, from which a few new compounds are isolated and investigated as potential bioactives, including anti-inflammatory and multi drug resistance reversal (21-24). Comparative distribution of chemical constituents in different parts *viz.*, leaves, seed, bark, fruit is mentioned in Fig. 4. There are activities of compounds which are known as steroids that are a type of organic compound having the characteristic molecular structure. The medicinal significance of each chemical constituent is mentioned in Table 3.

Bioactive limonoids and pharmacological potential of *C. tabularis* bark

Structurally diverse bioactive barks of Chukrasia gave a series of limonoid compounds of phragmalin type. Traditionally, the bark has been used in India and southern China as astringent, antidiarrheal and anti-flu (8). Phytochemical investigations have led to the identification of various structurally unique

Table 2. Properties of bioactive constituents of *Chukrasia tabularis*

Anti-Inflammatory & Antioxidant Compounds	Antimicrobial & Antifungal Agents	Cytotoxic & Antimalarial Compounds	Immune-Boosting & Metabolic Regulation
Quercetin Tabularin Tannic acid	Scopoletin Cedrelone Tannic Acid Melianone	Cedrelone Melianone	Sitosterol

Sourced from Ref. (43, 64).

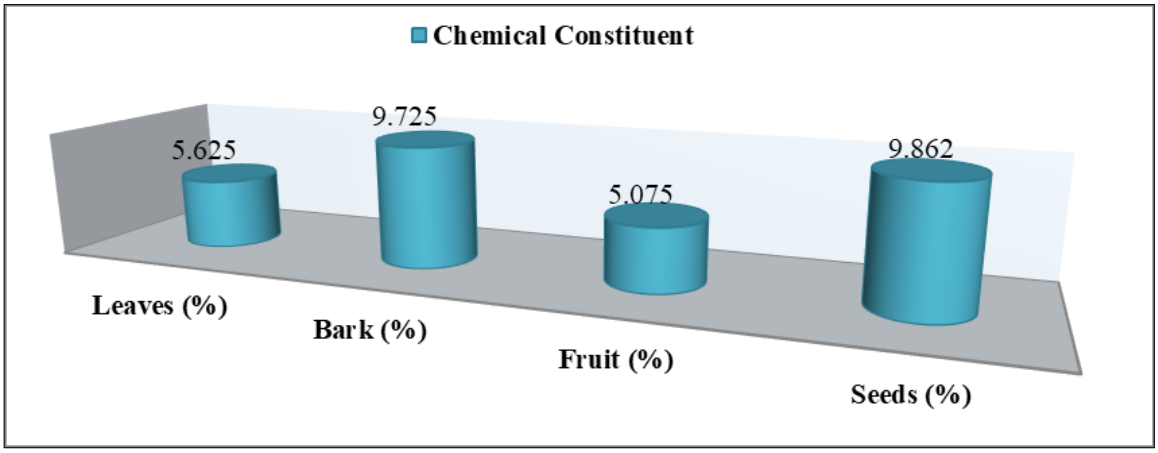

Fig. 4. Comparative distribution of chemical constituents in different parts of *Chukrasia tabularis*. Sourced from Ref. (22, 25).

Table 3. Medicinal significance of *Chukrasia tabularis* primary constituents

Primary constituents	Medicinal significance
Sitosterol	Helps in reducing cholesterol absorption, possesses anti-cancer potential and supports cardiovascular health
Quercetin	Protects against oxidative stress, lowers blood pressure, boosts the immune system and exhibits potential anti-cancer activity
Scopoletin	Used in treating hypertension, inflammation-related disorders and microbial infections. It also shows potential antidepressant effects
Cedrelone	Effective against bacterial and fungal infections, exhibits anticancer properties and has potential in malaria treatment
Tannic acid	Used for treating diarrhoea, wound healing and as an antimicrobial agent. It also helps in detoxification
Tabularin	Protects liver cells, reduces oxidative stress and may be useful in managing inflammatory diseases
Melianone	Used in antifungal treatments, potential application in cancer therapy and exhibits activity against malarial parasites

Sourced from Ref. (32, 37, 54, 61).

phragmalin limonoids, including the standard phragmalin limonoids and their ortho ester derivatives (25), as well as 16-norphragmalin limonoids featuring a distinctive 13,14,18-cyclopropane ring (14). Studies have demonstrated that phragmalin limonoids exhibit diverse biological activities, including anti-feedant effects (26), antibacterial properties (27), potassium channel-blocking activity (19) and anti-inflammatory potential (28). The limonoids present in bark of Chukrasia and the structures of compounds were determined using spectroscopic techniques, including NMR, IR and mass spectrometry, concluded with isolation of two newly identified phragmalin-type limonoids, Tabularisin Q and Chuktabularin Y, along with 22 previously known limonoids was investigated (29). In addition, the study notes the importance of its findings regarding the study of anti-inflammatory research. The anti-inflammatory properties of all limonoids were assessed *in vitro* using RAW 264.7 cells by measuring nitric oxide production induced by lipopolysaccharide. Among them, limonoids 8, 9, 1 and 18 demonstrated notable activity, with inhibition rates of 4.32, 11.28, 13.13 and 10.40 µM, respectively. These results indicate their potential for development as therapeutic agents for inflammatory diseases. The histidine point reversion assay to examine the antimutagenic properties of Chickrassy methanol extract (30). HPLC analysis identified catechin, quercetin and rutin as key compounds responsible for its antimutagenic properties which involves testing the extract against 4-nitro-o-phenylenediamine, sodium azide and 2-aminofluorene in TA98 and TA100 strains of *Salmonella typhimurium* which resulted in stronger desmutagenic activity compared to bioantimutagenic effects. The methanol extract was most effective in the TA98 strain, while the ethyl acetate fraction exhibited significant effects in the TA100 strain. The impact of different Chickrassy extracts and subfractions on peroxyl radical-induced damage to polyunsaturated fatty acids was investigated in the study (31) which correlated the role of polyphenols and polyphenol-rich plant fractions with the report of previous study (32) in protecting the lipid peroxidation mechanism by scavenging free radicals or chelating metal ions. The *C. tabularis* leaves key bioactive compounds identified with their chemical classification, biological functions and extraction methods are summarized (Table 4). Liver homogenate was used to assess lipid peroxidation, with malondialdehyde production serving as a marker of oxidative stress. The ethyl acetate fractions from the bark and leaves of Chukrasia showed the highest protective effects, inhibiting lipid peroxidation by 83.02 % and 88.62 %, respectively, supporting its potential use in Ayurvedic formulations. Luo et al. (33) has clearly depicted that the series of novel and structurally related phragmalin type limonoids with medicinal significance can be extracted using various methods as in correlation with the previous study (29). The stem bark of *C. tabularis* var. velutina led to the isolation of new C-15-acyl 16-norphragmalin-type limonoids, chuktabrins C-J and chuktabularins U-X. Their structures were determined through spectroscopic analysis, with the absolute configuration of compound 1 confirmed by single-crystal X-ray diffraction. A proposed biosynthetic pathway provided insights into their formation. These limonoids demonstrated notable anti-inflammatory activity, with IC50 values ranging from 2.40 to 16.90 µM against LPS-induced nitric oxide production in macrophage cells which has a correlated with the previous study (32). The bark of plant exudate the pinkish red colourant shows the remarkable nature as dye might possess various industrial applications.

Phytochemical composition and therapeutic potential of *C. tabularis* seeds

The seeds of the Jamaican cedar, also known as Indian mahogany, are flat and have a brown, membranous wing that is about twice as long as its body. These seeds are relatively rich in proteins, bioactive compounds and oil and are of high level of value for medicinal, cosmetic and industrial purposes. Chemically, they contain many compounds such as limonoids

Table 4. Bioactive compounds and its extraction in *Chukrasia tabularis* leaves

Bioactive Compounds	Chemical Class	Biological Function	Solvent Extract Used	References
Chuktabrin A, B	Limonoids	Antimicrobial, anti-inflammatory	Ethanol	49
Quercetin, Rutin, Epicatechin	Flavonoids	Strong antioxidants, anti-diabetic	Methanol	50
Gallic acid, Catechins	Phenolic acids	Reduces oxidative stress, DNA protection	Ethyl acetate	30
Tannins	Polyphenols	Astringent, antibacterial, anti-inflammatory	Water & methanol	

Sourced from Ref. (30, 49, 50).

and its derivatives, terpenoids and phenolic compounds, all of which are their major contribution to their medicinal value (34). The seeds contain limonoids, phragmaline and m exicolide group, which are known to overcome multidrug resistance in cancer cells specifically in MCF-7/DOX (3, 22). The compounds have also been shown to increase chemotherapy outcomes by overcoming drug resistance. The plant is recognized as being rich in other phenolic compounds with antioxidant properties. Having a high number of phenolic compounds and high antioxidant activity is strongly associated with the ability of this plant to be developed as a natural antioxidant drug (35). In addition, limonoids from *C. tabularis* possess outstanding anti-inflammatory properties. They had an excellent modesty to decrease the creation of pro inflammatory mediators like nitric oxide (NO), tumor necrosis factor alpha (TNF-α) and interleukin 6 (IL-6) by inhibiting important signaling pathways such as NF-κB and JAK2/STAT3 (24, 36). *C. tabularis* is a phytochemical rich plant having a diversity in limonoids and triterpenoids isolated from the leaves, stems and seeds. Applications that have been studied for these compounds include treatment of inflammation or as antimicrobial agents (37, 38). The previous study has depicted pharmacological potential because of its activity against multidrug resistance and strong anti-inflammatory, antioxidant and antimicrobial activities (22, 24, 35, 36). Antioxidant activity of the plant is very closely related to its high phenolic content, while anti -inflammatory activity of the plant is related mostly to limonoids. This corresponds with *C. tabularis* being a valuable source of bioactive compounds with many therapeutic applications (38). Besides unique limonoid structures, such as C-15-acyl phragmalin derivatives, the plant may serve as a source of the development of novel therapeutic agents (15, 39). Flavonoid compounds are abundant in the seeds and are known to be strong antioxidants. This is because the total phenolic content of *C. tabularis* is very high, probably indicating a potential natural source of antioxidants for use in pharmaceutical applications (40). The high amounts of phenolic compounds documented for these specimens and for Spanish plants are well related to the plant antioxidant activity and are a mark of future pharmacological ecology bestowed on this species. The limonoids present in its richness are designed to provide the anti-inflammatory effect largely. Studies further suggest that the plant limonoids inhibit the production of inflammatory mediators, such as nitric oxide, TNF-α and interleukin 6, by the macrophages (24, 36).

Much interest is being focused on the extraction and application of plant oils particularly from seeds, due to their valuable properties (41). The polyphenols, phytochemicals and bioactive compounds contained in these oils are very potent antioxidants. Their diverse applications include the food, pharmaceutical, cosmetic and agricultural industries due to their antimicrobial, anticancer, anti-inflammatory and immune modulatory effects (42). Jamaican cedar is rich in terpenes with potent antimicrobial and anticancer properties. Their composition varies depending on the species and environment but systematically exhibits bioactive potential (43).

Phytochemical diversity and therapeutic potential of *C. tabularis* leaves

C. tabularis has gained attention for its potential health benefits due to its complex phytochemical composition (29). While the bark and seeds of *C. tabularis* have been extensively studied, its leaves contain a variety of bioactive compounds that exhibit promising medicinal properties (44). The phytochemical profile of *C. tabularis* leaves includes Flavonoids: quercetin, kaempferol, catechin (45), Alkaloids: chukrasin and chuktabrin (46), Tannins: ellagitannins and gallotannins (47), Terpenoids: limonene, β-caryophyllene (48), Limonoids: tabularisin and chuktabularin (36). The plant's medicinal properties are contributed by these phytochemicals. The flavonoids and tannins present in *C. tabularis* leaves prevent the free radicals and reduce the oxidative stress (44). The leaf extracts possess excellent DPPH and ABTS radical scavenging properties has been shown in studies (45). Its leaves contain many of bioactive substance like flavonoids, limonoids, tannins, coumarins and sterols. Two novel limonoids, chuktabrin A and B, isolated from the leaves are noted for their unusual structures and are associated with their biological activity (49). Quercetin, rutin and epicatechin have also been identified as flavonoids in the plant and therefore the plant appears to have antioxidant potential (50). The leaves also contain flavonoids, phenolic acids like gallic acid and catechins that are known to reduce oxidative stress as well as cellular damage. The astringent properties of the leaves are due to the presence of tannins (30). These phytochemicals work collectively to enhance the pharmacological significance of *C. tabularis* leaves. Table 5 is for the mention of phytochemical composition of different parts of *C. tabularis*. Limonoids and flavonoid content of *C. tabularis* leaf has been associated with their anti-inflammatory properties (36). Inhibition of nitric oxide production in RAW 264.7 macrophage cells has been shown in experiments (46), suggesting possible uses as anti-inflammatory disorders. *C. tabularis* extracts have been indicated to be effective against *Escherichia coli*, *Staphylococcus aureus* and *Candida albicans* (47). Their antibacterial and antifungal properties are due to presence of alkaloids and terpenoids. There have been recent studies that show the cytotoxic effects of *C. tabularis* leaf extracts on different kinds of cancer cell lines, breast and liver cancer cells (48). The apoptosis induction and tumor growth inhibition role of limonoids and flavonoids is very important (45). *C. tabularis* leaf extracts have been thought to be hepatoprotective and are suggested to reduce liver damage causing toxic substances (46). Polypharatics and alkaloids are responsible for the regulation and detoxification of the liver and for the presence. Studies investigating the hepatoprotective of *C. tabularis* are, however, limited, however, its strong antioxidant and anti-inflammatory property suggests it could have potential hepatoprotective effects. And the phytochemicals from the plant

Table 5. Phytochemical composition of different parts of *Chukrasia tabularis*

Chemical Constituent	Leaves (%)	Bark (%)	Fruit (%)	Seeds (%)
Total Phenolics	12.5	18.3	10.2	22.8
Flavonoids	8.7	10.1	6.5	14.2
Tannins	5.4	15.2	7.1	4.8
Saponins	3.2	4.8	2.1	5.6
Alkaloids	4.5	9.6	3.8	6.9
Terpenoids	6.1	12.0	5.7	11.3
Limonoids	2.9	5.5	4.1	9.8
Steroids	1.7	2.3	1.1	3.5

Sourced from Ref. (5-7).

may help to protect it from hepatic disorders, by mitigating oxidative stress, reducing inflammation, factors chief in liver damage. However, further experimental and clinical studies are necessary to fully understand the mechanisms underlying its hepatoprotective activity (45). It possesses various ethnobotanical, ethnomedicinal and biopesticidal benefits which has been explored in studies (51) in assessing its potential in phytochemical profiling and antimicrobial properties, which shown results as the methanol extract demonstrated the highest carbohydrate content (45.10 %) and exhibited the most potent antimicrobial effects, with notable inhibition zones and low MIC values. Various solvent extracts exhibit high free radical scavenging activity, with the ethyl acetate fraction showing the strongest effect due to its high phenolic content (52). These properties make the leaves valuable in mitigating oxidative stress, which is a major factor in aging and chronic diseases. Additionally, the leaves have demonstrated protective effects against DNA damage. Studies using the Ames test reveal that *C. tabularis* leaf extracts can reduce mutagenicity caused by carcinogenic agents (7) which suggested its potential role in cancer prevention by minimizing oxidative damage at the genetic level. In addition to its disease prevention due to its ability to neutralize reactive oxygen species (ROS), *C. tabularis* leaves also demonstrates such therapeutic value. In addition to antioxidant activity, its leaves also possess antidiabetic, antimicrobial and cytotoxic effects in which they can regulate blood sugar levels by inhibiting α glucosidase and aldose reductase that are enzymes linked to carbohydrate metabolism. For this reason, they are considered promising natural alternatives for the management of diabetes (53). Besides, their anti-inflammatory properties, particularly the inhibition of 5-lipoxygenase, help to prevent progression of disease caused by metabolic disorders (53). Demonstrations of its extracts in strong antibacterial effects, especially against Gram positive bacteria, have made them a possible source of natural antimicrobial agents (10). The leaves of *C. tabularis* hold significant medicinal potential due to their diverse phytochemical composition. Properties such as their antioxidant, anti-inflammatory, antimicrobial, anticancer and hepatoprotective properties make them pertinent in pharmaceutical applications. It is time for future research to be conducted on validation of their therapeutic efficacy in clinical trials and the molecular mechanism of action.

Phytochemical investigations of *C. tabularis* fruits

This genus has been subject to phytochemical analysis for many structurally diverse limonoids within (54). Some of these compounds possess anti-inflammatory, α-glucosidase inhibitory, cytotoxic, antibacterial and insecticidal properties (15, 55). The capsule is firm, woody and upright ovoid or ellipsoid, 2.5-5 cm. Finally, upon maturation it splits into 3 to 5 valves for dispersal of seeds (56). Limonoids are particularly phragmalin-type limonoids of which the fruits are rich, which displayed moderate anti-inflammatory activity. *In vitro*, these compounds, including chuktabamalins A-E, inhibit the inflammatory mediator's nitric oxide and cytokines and therefore may be therapeutic in inflammatory conditions (23, 24, 36). Besides several known limonoids, several new compounds, containing chuktabamalins A-E and chuktabularoids A-J, were isolated. Advanced spectroscopic techniques revealed these compounds that were identified (21) and they identified the structural diversity, particularly in the D ring of these molecules (23). But the isolated limonoids including chuktabamalins have shown moderate to significant anti-inflammatory activity *in vitro*. How these compounds work consists in inhibiting the key inflammatory mediators and pathways like NF-κB; JAK2/STAT3; and iNOS/eNOS, which are crucial in the inflammatory response (23, 24, 36). A few limonoids have now been studied from *C. tabularis* fruit shells for their capacity of reversing multidrug resistance (MDR) in cancer cells, as stated in (21). The findings suggest that chuktabularoids may be able to increase the susceptibility of doxorubicin-resistant breast carcinoma cells to the medication, suggesting a promising role in the treatment of cancer. The high phenolic and flavonoid content in the plant parts, including the fruits, suggests their potential as natural antioxidants, which could be valuable in drug preparation and therapeutic applications (35). Three new triterpenoids, including two 19 (10→9β) abeo-tirucallane derivatives and a tirucallane-type triterpenoid, along with two known tirucallane -type triterpenoids, were isolated from *C. tabularis* fruit extract. Their structures were determined using NMR and MS analyses. Some compounds exhibited anti-inflammatory activity and cytotoxic effects against tumor cell lines (55). Chukrasia being the promising source of bioactive compounds, its potentiality in anti-inflammatory, MDR reversal and antioxidant activities proved to therapeutic agents.

Cytotoxic potential and anticancer properties of *C. tabularis*

The medicinal properties of Chukrasia extends its hand in showing the potentiality in cytotoxic ability. Various studies have explored the cytotoxic effects of *C. tabularis* constituents against different cancer cell lines. The previous research (24) identified tirucallane triterpenoids from the plant, which exhibited potent inhibitory effects against seven human cancer cell lines, including HepG2, Huh7, KB, H460, Hela, A-549 and MCF-7 suggested that the bioactive compounds present in *C. tabularis* may serve as promising candidates for the development of anticancer therapies (24). Beyond microbial defense, (10) also *revealed C. tabularis* leaves also show cytotoxic activity, with studies reporting their effectiveness against cancer cell lines. The presence of limonoids and flavonoids is believed to contribute to their ability to disrupt cancer cell growth and proliferation. The brine shrimp lethality assay, (9) showed the methanol crude extract of *C. tabularis* demonstrated an LC50 value of 1.58 mg/ml, indicating strong cytotoxic activity which has a correlation with the (10) study reported that the petroleum ether soluble fraction of the methanolic extract of *C. tabularis* leaves and bark displayed high cytotoxic potential with LC50 values of 0.0167 µg/mL and 3.89 µg/mL, respectively, compared to the standard vincristine sulphate. Phragmalin-type limonoids also evaluated for their cytotoxic activity in which tabulalide G exhibited moderate cytotoxic activity against the MCF-7 cancer cell line with an IC50 value of 20.4 µmol/L (28). Some compounds isolated from the fruit shells of *C. tabularis* showed potential in reversing multidrug resistance in cancer cells, enhancing doxorubicin susceptibility (21). The phragmalin derivatives isolated from *C. tabularis* seeds were tested for their cytotoxicity against various tumor cell lines, including SMMC-7721, MCF-7 and U2OS. These

compounds showed varying degrees of inhibition, suggesting their potential as anticancer agents (39). The bioactive compounds, particularly limonoids and flavonoids are known to interfere with cellular processes such as apoptosis and cell cycle regulation, which are crucial in cancer treatment. The specific mechanisms include the inhibition of nitric oxide production and modulation of inflammatory pathways, which are often linked to cancer progression (24, 36). These findings highlight its potential as a source of natural anticancer agents which also marks its remark in cytological field. Table 6 explains the efficacy-based classification of phytochemicals was tabulated.

Table 6. Efficacy-based classification of phytochemicals in *Chukrasia tabularis*

High Efficacy (>10%)	Moderate Efficacy (5-10%)	Low Efficacy (<5%)	References
Total Phenolics	Limonoids	Scopoletin	(48, 67)
Flavonoids	Alkaloids	Melianone	(23, 42)
Tannins	Cedrelone	Steroids	(37, 67)
Terpenoids	Sitosterol	Saponins	(23)

Economic significance

Alongside its medicinal significance, marks its importance as high-quality timber, decorative paneling (57), cabinet construction and flooring. Additionally, it is also used in carving, barrel production and the manufacture of paper pulp (58, 59). Its leaves and bark consist of around 22% tannins and gums and hence are important for use in the tanning process (60), whereas its flowers provide natural dyes red and yellow (58) are used in textile and cosmetic industries (61). High in bioactive compounds like limonoids, flavonoids and tannins that possess medicinal values (62). Utilized in classical medicine to treat fever and malaria (63). Exhibits antifeedant activity against pests of agriculture and justifies its use as an environmentally friendly insecticide (64). Utilized as a shade tree in coffee farms and works towards sustainable agroforestry (65). Used as green manure to improve soil fertility and crop yields (66). Increasingly, recent studies on the phytochemicals have further amplified knowledge of its varied constituents towards their potential in contemporary drug development (65). The synthesis of indigenous knowledge with contemporary scientific methods can open new avenues of using *C. tabularis* in the pharmaceutical, cosmetic and agricultural sectors.

Conclusion

C. tabularis is a very valuable medicinal plant with great pharmacological and industrial value. Its dense phytochemical content is responsible for its antimicrobial, antioxidant, anti-inflammatory and cytotoxic activities, making it a potential candidate for new drug formulations. Apart from medicine, the tree is of ecological and economic importance, providing high-quality wood, natural dyes and environmentally friendly pest control measures and finding application in agroforestry. Nonetheless, even though its uses are diverse, systematic pharmacological validation and safety tests are essential for its promotion on a broad scale in contemporary medicine. Clinical trials, standardization of extraction and cultivation in environmentally friendly practices are areas of future research that will lead to the harnessing of the maximum potential of *C. tabularis* as a mainstay of phytomedicine and sustainable industries. Future studies need to address thorough pharmacokinetic analyses, toxicity determinations and the establishment of standardized extraction protocols to unlock its full therapeutic potential. By filling the gap between ancient medicine and modern science, this lesser-explored species promises much for advancing global health and sustainable resource use.

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Authors' contributions

SS and IS conceptualized the study, literature collection, manuscript drafting and overall supervision. IS, JS, KTP and RR critical analyzed the phytochemical properties, data validation and manuscript revision. SS compiled the pharmacological aspects, data curation and interpretation of bioactive compounds. IS Reviewed and edited the manuscript, ensuring coherence and finalizing the submission. All authors have read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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