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Research Article

Analytical Study of *Terminalia catappa* L. Seeds from Central India: A Pharmacognostic, HPTLC, and FTIR-Based Approach

Arun Kumar [1], Dr. Sumedh Joshi *[2], Dr. Deepmala Pathak [3], Prof. Dr. Anil Shukla [4]

[1] PhD Scholar, Department of Botany, Mansarovar Global University, Sehore, Madhya Pradesh, India.

[2] MD (Ayu), PhD Scholar, All India Institute of Ayurveda, Gautampuri Awas, Sarita Vihar, Mathura Road, New Delhi, India.

[3] Associate Professor, Department of Botany, Mansarovar Global University, Sehore, Madhya Pradesh, India.

[4] Prof & Head- Department of Drvyaguna (Ayurved Pharmacology & Herbal Materia Medica) Mansarovar Ayurved Medical College, Hospital & Research Centre, Bhopal MP, India

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For Correspondence:

Sumedh Joshi, MD (Ayu), PhD Scholar, All India Institute of Ayurveda, Gautampuri Awas, Sarita Vihar, Mathura Road, New Delhi, India.

Abstract

Background- *Terminalia catappa* L., widely recognized in traditional medicine, has demonstrated hepatoprotective, antioxidant, and antimicrobial effects. However, phytochemical variability due to geographical differences hampers its standardization. This study aimed to establish a pharmacognostic and phytochemical profile of *T. catappa* seeds from the Central Indian Deccan Plateau, integrating modern spectroscopic and chromatographic tools.

Method- Mature seeds were collected from Bhopal, Madhya Pradesh, and authenticated. Pharmacognostic evaluations included transverse and powder microscopy, while physicochemical parameters (total ash, extractive values, moisture content) were measured per WHO and Ayurvedic Pharmacopoeia guidelines. Phytochemical constituents were identified via standardized tests on methanolic and aqueous extracts. Soxhlet extraction estimated total fat content. Fourier-transform infrared (FTIR) spectroscopy and high-performance thin-layer chromatography (HPTLC) were employed for molecular and marker compound analysis

Results-Microscopic analysis revealed characteristic features such as xylem tracheid, oil globules, stone cells, and calcium oxalate crystals. Physicochemical analysis yielded total ash (4.54%), alcohol-soluble extractive (16.39%), and moisture content (2.29%). Phytochemical screening confirmed the presence of alkaloids, flavonoids, proteins, and saponins, with notable absence of tannins. HPTLC detected β-sitosterol (255–268.7 µg/mL) with high reproducibility (CV = 3.69%). FTIR spectra revealed functional groups corresponding to phenolics, flavonoids, fatty acids, esters, and proteins.

Conclusion-This is the first standardized pharmacopeial profile of *T. catappa* seeds from Central India. Integration of classical pharmacognosy with FTIR and HPTLC establishes a replicable quality control framework for geographically distinct ecotypes. These findings support the nutraceutical and therapeutic potential of *T. catappa* seeds and lay the groundwork for future bioactivity validation and industrial application.

Keywords: FTIR spectroscopy, HPTLC, Pharmacognostic evaluation, Phytochemical profiling, Terminalia catappa.

1. INTRODUCTION

Terminalia catappa L. (Combretaceae), commonly known as tropical almond or Indian almond, is a pantropical tree species with significant ethnomedicinal importance. Traditionally, its seeds (Kath-badam) have been utilized in Ayurveda, Siddha, and folk medicine systems across Asia, Africa, and Latin America for treating inflammatory conditions, hepatic disorders, and microbial infections, attributed to their rich repertoire of bioactive compounds including tannins, flavonoids, triterpenoids, and fatty acids[1,2]. Modern pharmacological studies have validated these applications, demonstrating hepatoprotective, antioxidant, and antimicrobial properties in vitro and in vivo[3,4]. Despite this therapeutic potential, the species faces critical challenges in quality standardization due to pronounced geographical variations in phytochemical composition. Research indicates up to 30% variability in key metabolites (e.g., tannins, fatty acid profiles) across different ecoregions, undermining reproducibility in clinical applications[5,6]. Furthermore, comprehensive pharmacopeial standards specific to seed materials remain underdeveloped, hindering regulatory compliance and commercial utilization[7].

The need for region-specific pharmacognostic profiling is paramount. Environmental factors—including soil

composition, precipitation patterns, and temperature regimes—significantly modulate secondary metabolite synthesis in medicinal plants[8]. For *T. catappa* seeds, the absence of validated quality control protocols for Central Indian ecotypes (notably the semi-arid Deccan Plateau) represents a critical research gap. This region's distinct agroclimatic conditions may yield unique phytochemical adaptations with implications for bioactivity[9]. Moreover, conventional quality assessment methods often lack the sensitivity to resolve complex plant matrices, necessitating integration of advanced analytical techniques to establish definitive biomarkers[10].

To address these gaps, this study employs an integrated analytical framework combining classical pharmacognosy, phytochemical screening, and modern spectroscopic validation. Pharmacognostic evaluation includes determination of ash values, extractive yields, and moisture content according to World Health Organization (WHO) guidelines[11]. Phytochemical profiling targets alkaloids, flavonoids, tannins, proteins, and saponins using standardized solvent extraction protocols. Fourier-transform infrared (FTIR) spectroscopy provides molecular-level characterization of functional groups, while high-performance thin-layer chromatography (HPTLC) with gallic acid fingerprinting establishes polyphenol benchmarks. Soxhlet extraction quantifies lipid content to assess nutraceutical potential. This multidisciplinary approach bridges traditional knowledge with contemporary analytical rigor.

Future research should prioritize correlating the identified physicochemical and phytochemical parameters with specific bioactivities through in vivo studies. Clinical validation of hepatoprotective and antidiabetic effects—historically ascribed to *T. catappa* seeds—would strengthen evidence-based applications. Additionally, exploring industrial scalability of seed oil extraction and stable formulation development could unlock economic potential. The influence of seasonal variations on metabolite profiles warrants longitudinal studies to optimize harvesting protocols.

This work contributes to the field by establishing the first standardized pharmacopeial profile for Central Indian *T. catappa* seeds, directly supporting WHO objectives for herbal medicine quality assurance. The methodological integration of classical techniques with FTIR spectroscopy creates a replicable blueprint for analysing geographically variable medicinal plants. By defining region-specific biomarkers, this study enables precise quality control in phytopharmaceutical manufacturing, facilitates intellectual property protection for unique ecotypes, and advances the scientific validation of traditional medicine systems.

2. MATERIAL AND METHODOLOGY-

2.1 Collection of plant material-

The sample of *Terminalia catppa* seeds was collected from its natural habitat, from Mansarovar Global University, Bilkisganj, Bhopal Division, Madhya Pradesh (Coordinates- 23°04'40"N 77°15'18"E). The sample was authenticated at Taxonomy and Herbarium Laboratory of the Regional Raw Drug Repository, Trance Ganga Plain Region All India Institute of Ayurveda Sarita Vihar, New Delhi (Voucher specimen No. RRDR/AIIA/169) and sample specimen is preserved at the same institute. The sample was then shade dried and made into powder for the further analysis.

2.2 Microscopic analysis

2.2.1 Transverse section[12]

Mature seeds were first soaked in water to facilitate softening. Thin cross-sections were obtained using a sharp blade and mounted on glass slides with glycerine. The prepared sections were examined under a light microscope to analyse internal anatomical features, including the seed coat, endosperm, embryo, testa , parenchyma cells, oil cells and crystal

2.2.2 Powder microscopy[13]

A small quantity of the seed powder was mounted on a glass slide with a suitable reagent (i.e. glycerine). The slide was covered with a coverslip and examined under a microscope to observe diagnostic characters such as xylem tracheid, annular thickenings, starch grains, stone cell, ramified pits, oil globules, fibbers, and crystals.

2.3 Physicochemical analysis[14]

The sample was then subjected to the physicochemical analysis as per the methods given by Ayurveda Pharmacopeia of India. The analysis was composed of five parameters viz, total ash value, acid-insoluble ash value, alcohol soluble extractive value, water soluble extractive value and loss on drying estimation. Analysis was done in triplets and the average value of the three observations were taken as a final result.

2.3.1 Estimation of total ash value

Accurately weigh 2 to 3 grams of the air-dried, powdered drug into a previously ignited and tarred silica crucible. Incinerate gently at first and then at a temperature not exceeding 450°C until the residue becomes white, indicating the absence of carbon. Cool the crucible in a desiccator and weigh. Calculate the total ash content as a percentage of the air-dried drug.

2.3.2 Estimation of acid-insoluble ash value

To the crucible containing the total ash, add 25 ml of dilute hydrochloric acid (2N) and boil gently for 5 minutes. Filter the mixture through an ashless filter paper, collecting the insoluble matter. Wash the residue with hot water until the filtrate becomes neutral. Transfer the filter paper with residue to the original crucible and incinerate to constant weight. Cool in a desiccator and weigh. Calculate the acid-insoluble ash as a percentage of the air-dried drug.

2.3.3 Estimation of alcohol soluble extractive value

Macerate 5 grams of the air-dried, coarsely powdered drug with 100 ml of alcohol (95% v/v) in a closed flask for 24 hours. Shake the mixture frequently during the first 6 hours and allow it to stand undisturbed for the

next 18 hours. Filter the mixture quickly to prevent evaporation of alcohol. Pipette out 25 ml of the filtrate, evaporate to dryness in a tarred flat-bottomed dish, dry at 105°C to constant weight, and weigh. Calculate the alcohol-soluble extractive value as a percentage of the air-dried drug.

2.3.4 Estimation of water soluble extractive value.

Macerate 5 grams of the coarsely powdered air-dried drug with 100 ml of chloroform water for 24 hours, shaking frequently during the first 6 hours and allowing to stand for 18 hours. Filter, evaporate 25 ml of the filtrate to dryness in a tarred dish, dry at 105°C to constant weight, and weigh. Express the water-soluble extractive value as a percentage of the air-dried drug.

2.3.5 Estimation of loss on drying

Weigh accurately 2 grams of the powdered drug and place it in a tarred evaporating dish. Dry the sample in an oven at 105°C until a constant weight is obtained. Cool in a desiccator and weigh. Calculate the percentage loss in weight with reference to the air-dried substance. This value represents the moisture content and volatile matter present in the drug.

2.4 Primary phytochemical analysis[15]

The dried powder of seeds was then extracted in chloroform-water and methanol (1 gm in 10 ml of solvent) by cold maceration method. The prepared extracts were then subjected to the primary phytochemical analysis by using standardized methods.

2.4.1 Test for alkaloids

To a small quantity of the extract, add a few drops of dilute hydrochloric acid and filter. To the acidic filtrate, add Dragendorff's reagent (solution of potassium bismuth iodide). The appearance of an orange or orange-red precipitate indicates the presence of alkaloids.

2.4.2 Test for tannins

To 2–3 ml of the extract, add a few drops of **1**% ferric chloride solution**.** A blue-black or greenish-black coloration confirms the presence of tannins.

2.4.3 Test for flavonoids

To the extract, add a few fragments of magnesium ribbon, followed by a few drops of concentrated hydrochloric acid. The development of a pink, red, or orange coloration indicates the presence of flavonoids.

2.4.4 Test for proteins

Add Millon's reagent to a small amount of the extract and heat gently. A white precipitate that turns red upon heating confirms the presence of proteins

2.4.5 Test for saponins

Dilute 1 ml of the extract with 20 ml of distilled water in a test tube and shake vigorously for 15 minutes. The formation of a stable, persistent froth indicates the presence of saponins.

2.5 Estimation of total fat content

To estimate total fat in a herbal sample using a Soxhlet apparatus, accurately weigh 2–5 grams of the dried, powdered sample and place it in a pre-weighed extraction thimble. Insert the thimble into the Soxhlet extractor attached to a round-bottom flask containing petroleum ether (boiling point 40–60 °C) or hexane. Connect a condenser on top and heat the setup so the solvent refluxes and repeatedly extracts the fat over 6–8 hours. After extraction, evaporate the solvent from the flask using a rotary evaporator or gentle heating. Dry the flask in an oven, cool it in a desiccator, and weigh it to determine the amount of fat extracted by difference in weight.

2.6 HPTLC analysis for the estimation of beta-sitosterol[16]

The estimation of ß-sitosterol in *Terminalia catappa* seed extract was carried out using High-Performance Thin-Layer Chromatography (HPTLC). Standard ß-sitosterol solutions of known concentrations and the methanolic extract of *T. catappa* seeds were applied to a silica gel 60 F_{254} HPTLC plate using a Linomat 5 applicator. The applied volumes ranged from 0.5 µL to 2.0 µL for the sample and up to 3.5 µL for the standard. The plate was developed in a pre-saturated twin trough chamber with a mobile phase consisting of Toluene:EthylAcetate:Formic Acid (19.6:2.6:0.2, v/v/v). After development, the plate was dried at room temperature and visualized under white light, 254 nm, and 366 nm wavelengths using a TLC Visualizer.

The developed plate was scanned using a TLC Scanner 4 at 254 nm and 366 nm to obtain chromatographic profiles. For better visualization and quantification, the plate was derivatized with 10% methanolic sulphuric acid and heated at 100 °C for 3 minutes. The derivatized plate was then scanned at 540 nm, and the peak areas were recorded. A calibration curve was generated using the standard ß-sitosterol, and the amount of ß-sitosterol in the sample was quantified based on the regression equation. The analysis was performed and processed using visionCATS software, ensuring system suitability and valid diagnostics throughout the evaluation.

2.7 FTIR Analysis[17]

The powdered sample was then subjected to FTIR analysis as per the Standard Operating Procedure designed by Regional Raw Drug Repository, All India Institute of Ayurveda, New Delhi. Universal Attenuated Total Reflectance (UATR) method was adopted to perform the analysis.

3. OBSERVATION AND RESULTS

3.1 Microscopic analysis

3.1.1 Transverse section of the seed-

The transverse section of *T. catappa* seed observed under a microscope showing an elliptical outline, hardened testa externally, surrounded by a mesocarp consisting of parenchymatous tissue. The embryo is seen in the centre of the nourishing endosperm. At 10X magnification, loosely arranged parenchymatous cells with thin walls are seen, featuring clear intercellular spaces. At increased magnification (40X), parenchyma

cells become distinctly visible alongside oil cells and angular crystals. Observations are depicted in figure no 1 and 2

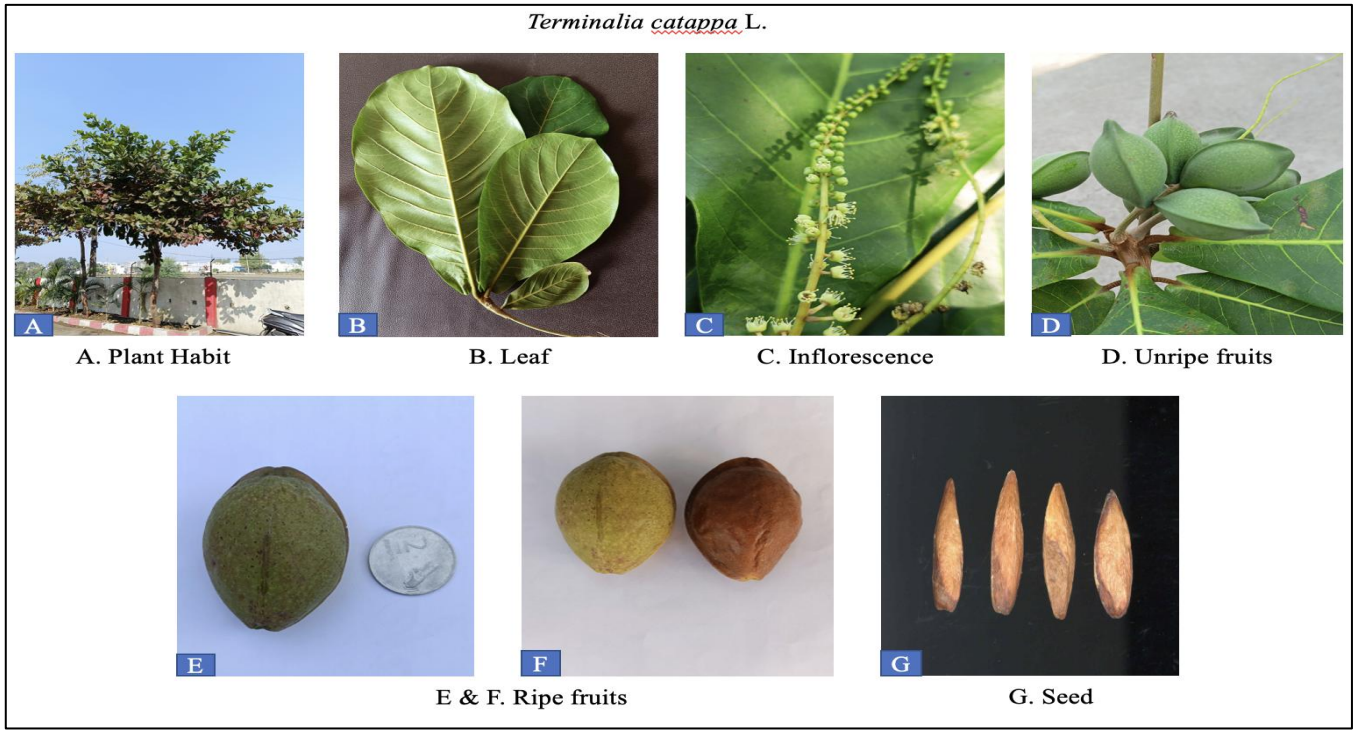


Figure 1: Macroscopic study of *Terminalia catappa* seeds.

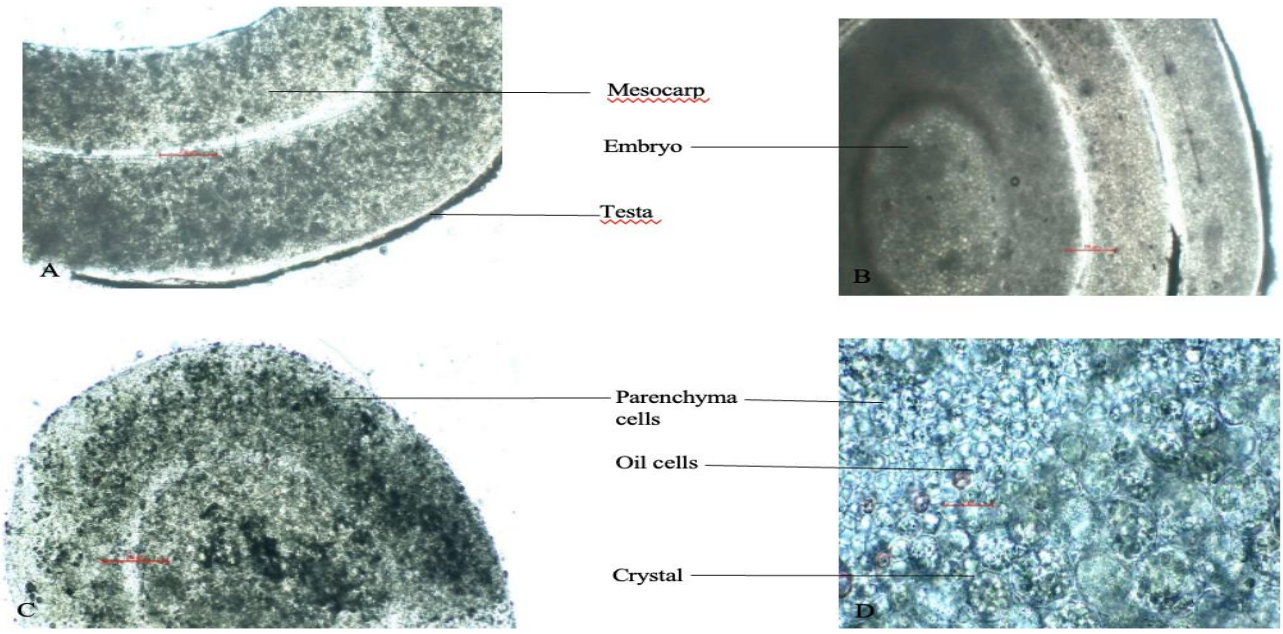


Fig no 2 . *Terminalia catappa*; Seed A.: T.S. at 10X showing elliptical outline, lignified tests, mesocarp; B: T.S. at 10X showing embryo; C: T.S. at 10X showing prenchymatous cells; D: T.S. at 40X showing parenchyma cells, oil cells, crystal.

3.2.2 Powder microscopy

The seed powder of *T catappa*, when stained with safranin and observed microscopically, reveals distinct anatomical features. Xylem tracheid with prominent annular thickenings are clearly visible, along with ramified pits characteristic of secondary xylem. Additionally, the presence of stone cells and calcium oxalate crystals is noted, providing structural rigidity and defence. Oil globules are evident, indicating the presence of lipid-rich components and fibres are also seen. These features collectively highlight the complex internal structure and diagnostic microscopic characteristics of the seed. Observations are depicted in figure no 3. And Figure no 4.

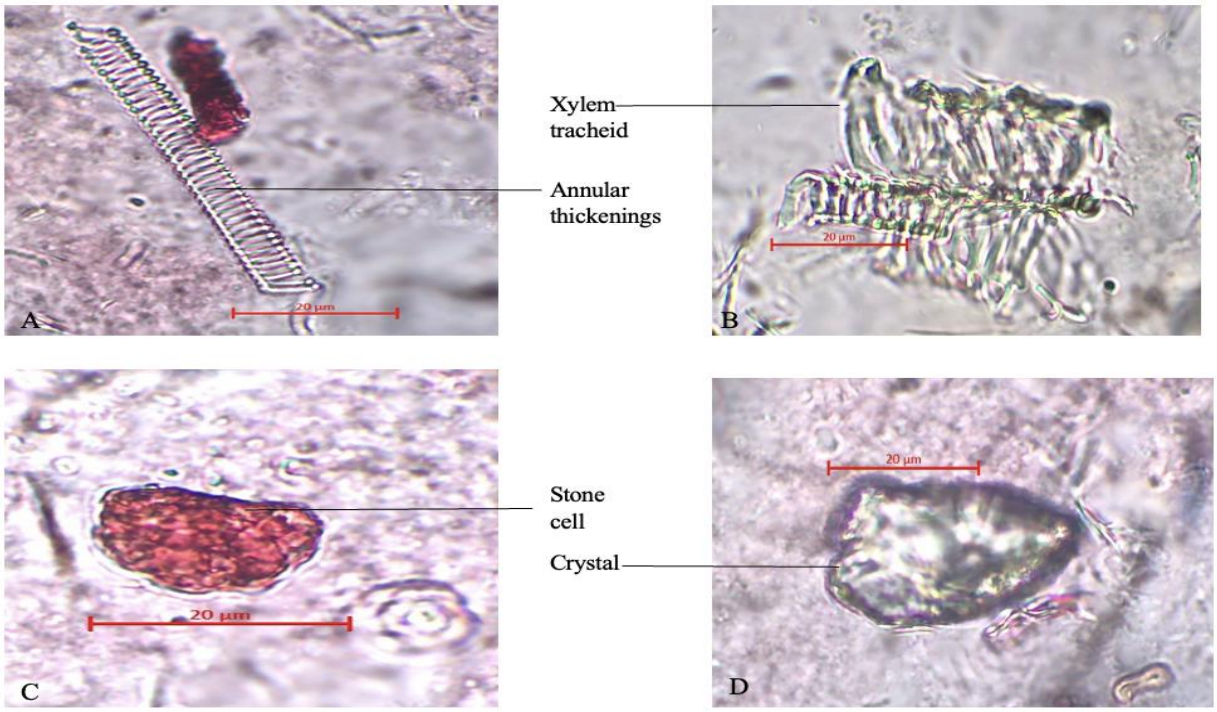


Fig. no 3. *Terminalia catappa*; Seed A.: Powder at 40X stained in safranin showing xylem tracheids with annular thickenings; B: Powder at 40X stained in safranin showing xylem tracheids; C: Powder at 40X stained in safranin showing stone cell; D: Powder at 40X stained in safranin showing crystal.

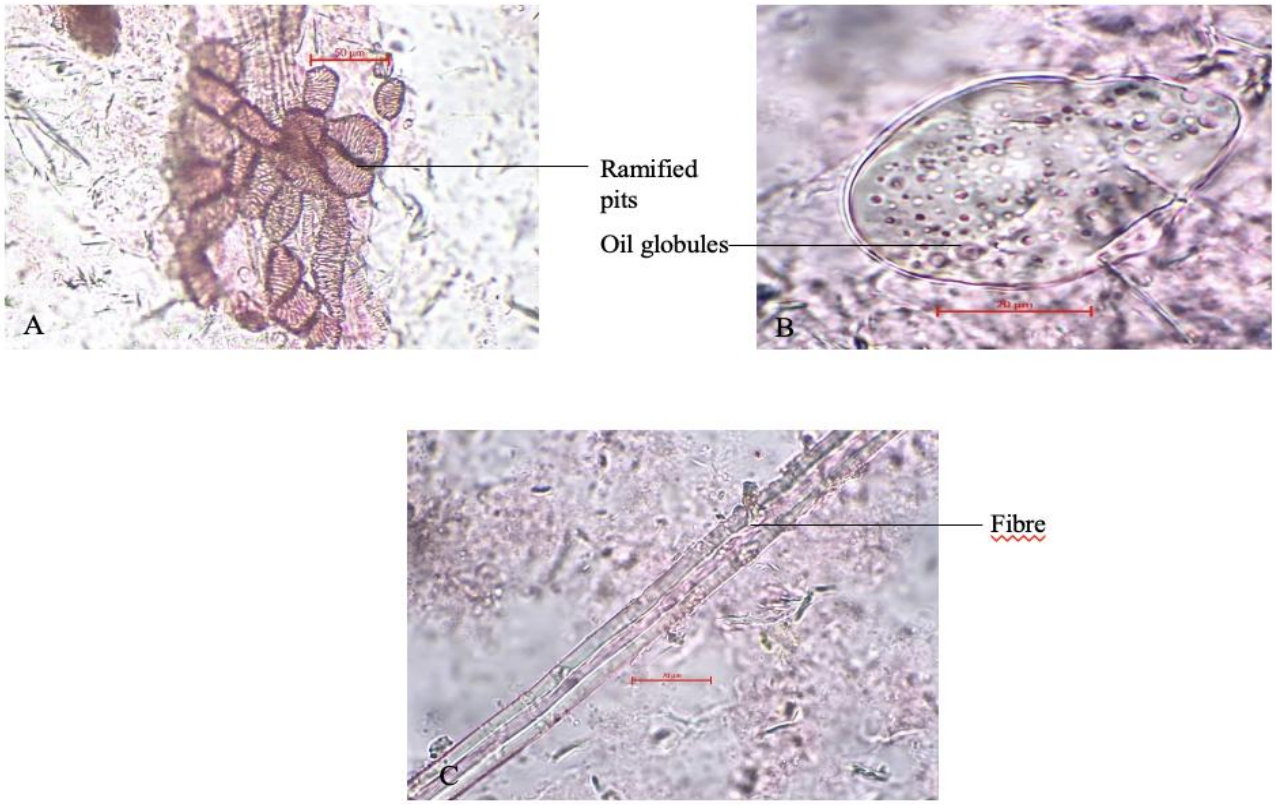


Fig.no 4. *Terminalia catappa*; Seed A.: Powder at 40X stained in safranin showing ramified pits; B: Powder at 40X stained in safranin showing oil globules; C: Powder at 40X stained in safranin showing fibres.

3.2 Physicochemical analysis

The final result was determined by calculating the mean of three independent observations to ensure accuracy and reproducibility. In the absence of specific data from recognized pharmacopoeias or official databases, previously published research studies were used as reference benchmarks for comparison and validation of the results. The results are depicted in table no 1

Table 1: Observations of physicochemical analysis

Parameter	Observed value
Total Ash	4.54%
Acid- insoluble Ash	0.20%
Alcohol soluble extractive values	16.39%
Water soluble extractive	9.42%
LOD	2.29%

3.3 Primary phytochemical analysis

Phytochemical analysis was performed in triplicate to ensure consistency and reliability of the results. Only those constituents that were consistently observed across all three replicates were considered as confirmed and included in the final findings. The detailed observations are presented in Table 2.

Table 2: Observations of phytochemical analysis

S.NO	Phytochemical class	Extract	
		Aqueous	Methanolic
1.	Alkaloids	+++	+++
2.	Tannins	-	-
3.	Flavonoids	-	++
4.	Proteins	+	++
5.	Saponins	++	+

3.4 HPTLC analysis

The HPTLC analysis of *Terminalia catappa* seed extract revealed the presence of ß sitosterol, as confirmed by matching Rf values and peak profiles with the standard. The derivatized plate, scanned at 540 nm, showed clear and distinct peaks corresponding to ß-sitosterol. Quantitative analysis using area calibration and linear regression (R = 0.998) indicated that the concentration of ß-sitosterol in the seed extract was 268.7 µg/mL for a 1.5 µL application and 255.0 µg/mL for a 2.0 µL application. The results demonstrated good reproducibility with a low coefficient of variation (CV = 3.69%), confirming the accuracy and reliability of the method for estimating ß-sitosterol content in *T. catappa* seeds. The observations are depicted in figure no 5 .

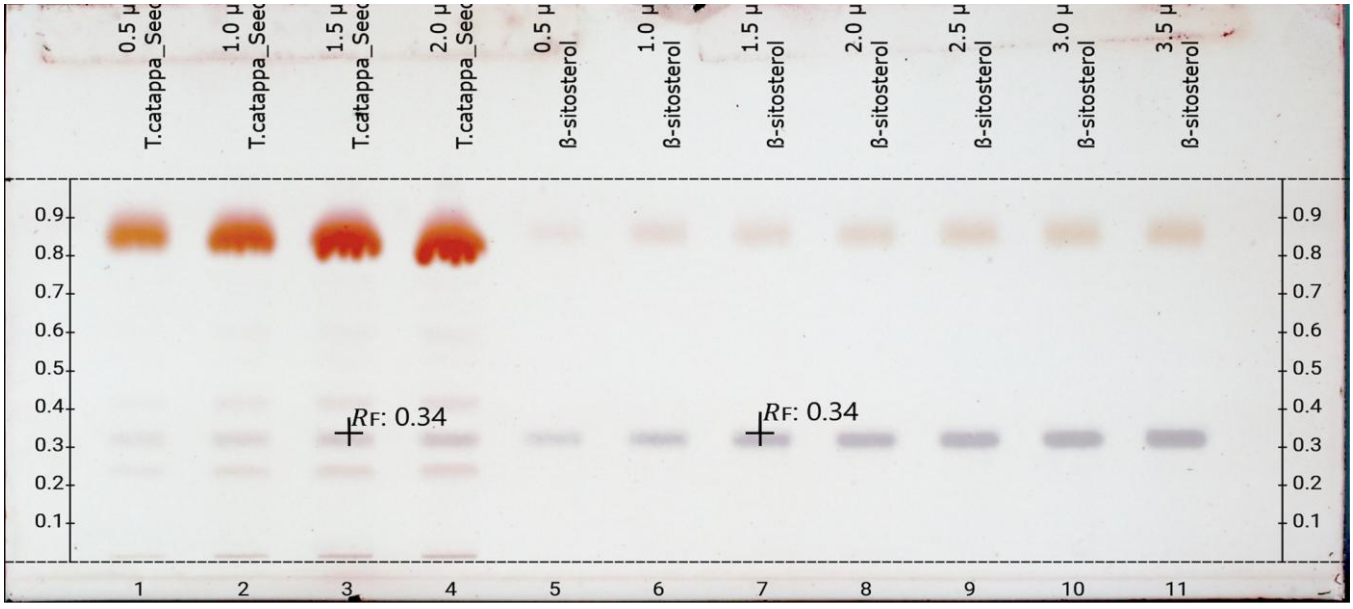


Figure 5: Quantification of Beta-sitosterol in *T. catappa* seed extract by using HPTLC technique.

3.5 FTIR analysis

The absorption peaks obtained from the FTIR spectroscopy (as shown in fig no 1) analysis were systematically compared with reference spectra and functional group correlation tables provided by Sigma-Aldrich. This comparison was conducted to identify the most probable functional groups associated with the observed wavenumber ranges, based on known characteristic absorption bands. The observations and results are depicted in Figure no 6 and table no 3.

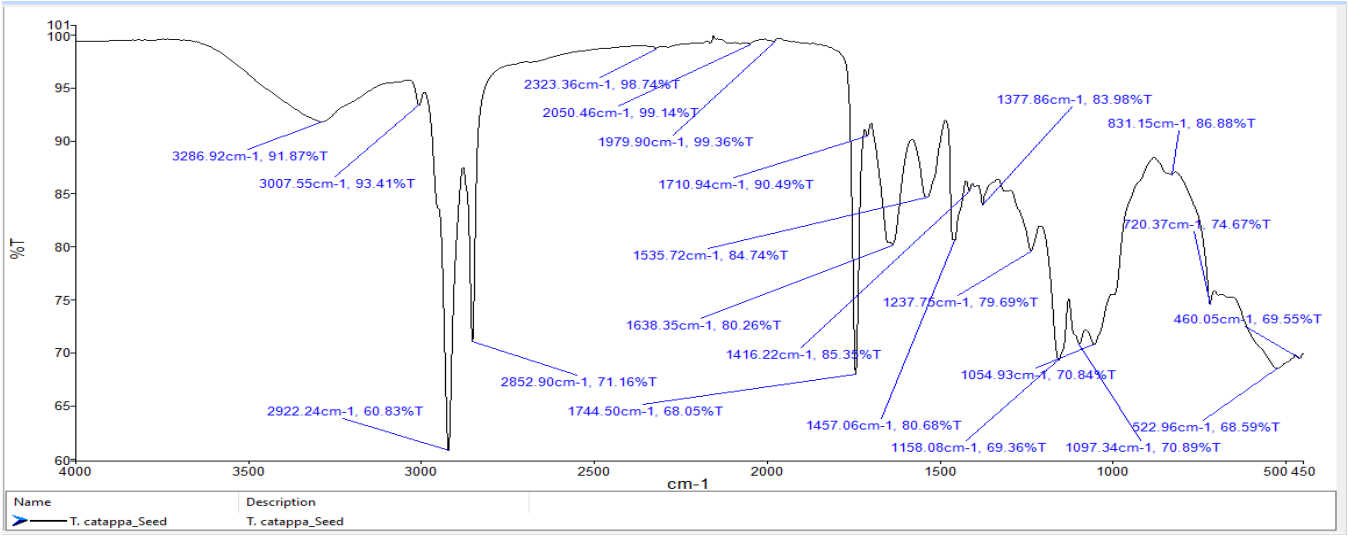


Figure 6: Peaks obtained after FTIR Spectroscopy of *T. catappa* seed using UATR method.

Table 3: Comparison of FTIR peaks to Sigma- Aldrich library.

Observed Wavenumber (cm^{-1})	Assignment	Functional Group	Probable Compound Class
3286.92	O–H/N–H stretching (broad)	Hydroxyl, amine groups	Phenolics, flavonoids, tannins, proteins
3007.55	=C–H stretch (aromatic)	Aromatic C–H	Flavonoids, lignins
2922.24	C–H asymmetric stretch	Aliphatic C–H	Fatty acids, lipids
2852.90	C–H symmetric stretch	Aliphatic C–H	Fatty acids, triglycerides
2323.36	Atmospheric CO_2 / trace C≡C	Possible contaminant or alkyne	Environmental CO_2 or minor components
2050.46	Aromatic overtone / N=C=O	Isocyanates / combination bands	Aromatic structures or minor phytoconstituents
1979.90	Aromatic overtone	C=C combination band	Aromatics, flavonoids
1744.50	C=O stretch (ester)	Carbonyl	Esters, lipids, fatty acid esters
1710.94	C=O stretch (acid/ketone)	Carbonyl	Carboxylic acids, tannins
1638.35	Amide I / C=C stretch	C=O, C=C	Proteins, polyphenols
1535.72	Amide II (N–H bend + C–N stretch)	Amide	Proteins, enzymes
1457.06	CH_2 bending	Aliphatic chain	Lipids, hydrocarbons
1416.22	O–H bending / C–C stretch	Phenolic OH / Aromatic	Phenolics, flavonoids
1377.86	CH_3 symmetric bend	Methyl group	Lignin, small phytochemicals
1237.75	C–O stretch	Ether, phenol	Flavonoids, tannins
1158.08	C–O–C stretch	Ester/ether	Glycosides, carbohydrates
1097.34	C–O or C–N stretch	Alcohol, amine	Sugars, alkaloids
1054.93	C–O stretch	Alcohol	Carbohydrates
831.15	=C–H out-of-plane bend	Aromatic ring	Substituted aromatics
720.37	$(CH_2)n$ rocking	Alkane chain	Long-chain fatty acids
522.96	Skeletal / ring deformation	Aromatic or aliphatic ring	Polyphenols, lignin
460.05	Ring deformation / metal–O	Aromatic skeleton / minerals	Lignin, inorganic residue

DISCUSSION

The present study provides a comprehensive pharmacognostic and phytochemical characterization of *Terminalia catappa* seeds collected from the Central Indian agroclimatic zone, particularly the Deccan Plateau region. This region is underrepresented in existing pharmacopeial data despite its distinctive environmental conditions, which likely influence secondary metabolite profiles. Notably, the study's integration of traditional microscopic techniques with advanced spectroscopic methods such as Fourier-transform infrared (FTIR) spectroscopy and high-performance thin-layer chromatography (HPTLC) establishes a critical baseline for quality assurance in herbal pharmacology. FTIR peaks indicative of polyphenols, fatty acids, proteins, and other bioactive compounds underscore the biochemical complexity of the seed matrix. These findings align with previous research that emphasizes the importance of geographic and environmental factors in phytochemical variability.[18]

Microscopic analysis, both transverse and powder-based, provided diagnostic anatomical markers, including xylem tracheids with annular thickenings, stone cells, oil globules, and calcium oxalate crystals. These structural features serve as robust identifiers of *T. catappa* seed tissues, aiding in the authentication and quality control of raw drug materials. Such microanatomical features have been reported as crucial for differentiating closely related taxa and detecting adulteration in crude drugs[19]. Moreover, the transverse section demonstrated a well-defined endosperm and embryonic region surrounded by a hardened testa, corroborating prior anatomical descriptions of the species[20]. These morphological attributes, together with physicochemical constants like total ash (4.54%) and alcohol-soluble extractives (16.39%), align with WHO parameters for evaluating herbal raw materials[21].

The primary phytochemical screening confirmed the presence of alkaloids, flavonoids, proteins, and saponins, with differential solubility in aqueous and methanolic extracts. Interestingly, tannins were absent, which is noteworthy given their prominence in *T. catappa* leaf and bark extracts as reported in earlier studies[22]. This suggests potential tissue-specific distribution of phenolic compounds and underscores the need for targeted studies focusing on seed-specific pharmacodynamics. The presence of lipophilic components, confirmed by Soxhlet extraction and FTIR bands corresponding to fatty acids (2922.24 and 2852.90 cm^{-1}), indicates the seed's nutraceutical potential. These lipids could harbor anti-inflammatory and hepatoprotective activities previously observed in other parts of the plant[23].

The estimation of total fat content using Soxhlet extraction revealed the presence of a significant proportion of lipid components within *T. catappa* seeds. Though the exact percentage is not numerically provided in the document, the clear observation of oil globules in powder microscopy and the use of non-polar solvents (such as petroleum ether or hexane) during Soxhlet extraction underscore the abundance of neutral lipids, essential fatty acids, and possibly unsaponifiable matter in the seed matrix. Previous studies have shown that *T. catappa* seeds are rich in unsaturated fatty acids—particularly oleic and linoleic acids—which contribute to anti-inflammatory, hepatoprotective, and cardioprotective properties[24].

The FTIR analysis employed in this study was pivotal in delineating the molecular architecture of bioactive compounds present in *T. catappa* seeds. Using the Universal Attenuated Total Reflectance (UATR) method, a broad spectrum of absorption peaks was recorded, each correlating with specific functional groups that denote the presence of diverse phytochemical classes. Notably, the broad absorption at 3286.92 cm^{-1} corresponds to O–H and N–H stretching vibrations, indicative of hydroxyl groups found in polyphenols, flavonoids, and proteins. This finding supports the earlier phytochemical tests that confirmed the presence of proteins and flavonoids .Aliphatic C–H stretching observed at 2922.24 cm^{-1} and 2852.90 cm^{-1} is consistent with the fatty acid and triglyceride components noted during fat extraction. These signals suggest the prevalence of long-chain hydrocarbons, possibly derived from seed oil constituents like palmitic, stearic, and linoleic acids. In addition, a sharp peak at 1744.50 cm^{-1} attributed to C=O stretching of esters and 1710.94 cm^{-1} of carboxylic acids further confirms the presence of lipid esters and free fatty acids, which are known to exhibit antioxidative and membrane-stabilizing effects.

The presence of amide bands—Amide I at 1638.35 cm^{-1} and Amide II at 1535.72 cm^{-1}—signifies peptide or protein content, corroborating with positive results in Millon's protein test during phytochemical screening. Additionally, the fingerprint region (1237.75–720.37 cm^{-1}) exhibited diverse bands corresponding to ether (C–O–C), aromatic (C–H out-of-plane bending), and CH_2 rocking vibrations, which suggest the presence of complex polysaccharides, lignins, and flavonoid derivatives[25]. Collectively, the FTIR spectra provided robust molecular evidence for the phytoconstituents identified through conventional tests and revealed additional minor components that may not have been detected via wet chemistry. This supports the growing consensus that FTIR, when used alongside chromatographic methods, offers a rapid, non-destructive, and chemically comprehensive profiling tool for herbal materials[26].

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Authors' contributions: Arun Kumar contributed to conceptualization of the study, methodology, experimental investigation, data curation, and preparation of the original draft.

Sumedh Joshi contributed to conceptualization, supervision, formal analysis, validation of results, critical revision of the manuscript, and served as the corresponding author.

Deepmala Pathak contributed to resource support, botanical authentication guidance, methodological inputs, and manuscript review and editing.

Anil Kumar Shukla contributed to supervision, expert input in Ayurveda understanding, validation of the study design and findings, and critical review of the manuscript.

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Ethical Approval: This study did not involve human participants, animal experimentation, or clinical intervention. Therefore, ethical approval was not required for this research work.

REFERENCES

1. Pereira A, Sumathy A, Usha K. Terminalia catappa: Ethnopharmacology and therapeutic potential. J Ethnopharmacol. 2018;227:26-35.
2. Chaudhary G, Goyal S, Poonia P. Ayurvedic applications of Terminalia catappa:A review. J Ayurveda Integr Med. 2020;11(3):312-8.
3. Fan YM, Xu LZ, Gao J, Wang Y, Tang XH, Zhao XN, et al. Hepatoprotective activity of Terminalia catappa L. leaves and its two triterpenoids. Am J Chin Med.2004;32(4):509-19.
4. Ko TF, Weng YM, Lin SB, Chiou RY. Antioxidant capacity of Terminalia catappa leaves extracts and its major flavonoids. Food Chem. 2007;100(4):1539-45.
5. Khan AV, Ahmed QU, Mir MR, Shakil S, Khan AA. Geographic variation in phenolic composition of Terminalia catappa L. leaves. Nat Prod Res. 2015;29(7):621-7.
6. Patra JK, Rath SK, Jena KB, Rathod VK, Thatoi HN. Chemical composition and antioxidant potential of Terminalia catappa Linn. fruit extracts. J Food Biochem. 2011;35(5):1530-41.
7. Ministry of AYUSH. The Ayurvedic Pharmacopoeia of India. Part I, Vol. IX. New Delhi: Government of India; 2016.
8. Harborne JB. Phytochemical Methods: A Guide to Modern Techniques of Plant Analysis. 3rd ed. London: Chapman & Hall; 1998.
9. Kumar V, Kumar M, Agrawal S, Singh S. Soil-climate-phytochemistry relationships of medicinal plants in Central India. Ind Crops Prod. 2019;142:111857.
10. Schulz H, Baranska M. Identification and quantification of valuable plant substances by IR and Raman spectroscopy. Vib Spectrosc. 2007;43(1):13-25. https://doi.org/10.1016/j.vibspec.2006.06.001
11. World Health Organization. Quality control methods for herbal materials. Geneva: WHO Press; 2011.
12. Trease GE, Evans WC. Pharmacognosy. 16th ed. Edinburgh: Saunders Elsevier; 2009. p. 545-547.
13. Wallis TE. Textbook of Pharmacognosy. 5th ed. New Delhi: CBS Publishers & Distributors; 2005. p. 123-145.
14. Government of India, Ministry of AYUSH. The Ayurvedic Pharmacopoeia of India, Part I, Vol. I. 1st ed. New Delhi: Department of AYUSH; 2001. p. 143-145.
15. Kokate CK, Purohit AP, Gokhale SB. Practical Pharmacognosy. 4th ed. Pune: Nirali Prakashan; 2005. p. 107-111.
16. Sharma H, Narshimhaji CV, Singh R. Relative estimation of beta-sitosterol in alcoholic extracts of roots and small branches of oroxylum indicum (L.) Kurz by HPTLC for plant part substitution, medicinal uses and conservation. Journal of Applied Research on Medicinal and Aromatic Plants. 2023 May 1;35:100496. https://doi.org/10.1016/j.jarmap.2023.100496
17. Joshi DD. FTIR spectroscopy: Herbal drugs and fingerprints. In Herbal Drugs and Fingerprints: Evidence Based Herbal Drugs 2012 Oct 3 (pp. 121-146). India: Springer India. https://doi.org/10.1007/978-81-322-0804-4_7
18. Khan AV, Ahmed QU, Mir MR, Shakil S, Khan AA. Geographic variation in phenolic composition of Terminalia catappa L. leaves. Nat Prod Res. 2015;29(7):621-7.
19. Wallis TE. Textbook of Pharmacognosy. 5th ed. New Delhi: CBS Publishers & Distributors; 2005. p. 123-145.
20. Akinsulire OP, Oladipo OT, Illoh HC, Mudasiru OM. Vegetative and reproductive morphological study of some species in the family Combretaceae in Nigeria. Ife Journal of Science. 2018 Aug 13;20(2):371-89. https://doi.org/10.4314/ijs.v20i2.18
21. World Health Organization. Quality control methods for herbal materials. Geneva: WHO Press; 2011.
22. Mwangi WC, Waudo W, Shigwenya ME, Gichuki J. Phytochemical characterization, antimicrobial and antioxidant activities of Terminalia catappa methanol and aqueous extracts. BMC Complementary Medicine and Therapies. 2024 Apr 2;24(1):137. https://doi.org/10.1186/s12906-024-04449-7 PMid:38566161 PMCid:PMC10986026
23. Gopalam R, Manasa V, Vaishnav SR, Daga P, Tumaney AW. Profiling of lipids, nutraceuticals, and bioactive compounds extracted from an oilseed rich in PUFA. Plant Foods for Human Nutrition. 2022 Mar;77(1):98-104. https://doi.org/10.1007/s11130-021-00945-0 PMid:35088213
24. Zannou O, Awad NM, Ballogou VY, Mohammed S, Miassi YE, Houngbédji M, Dossa KF, Abdoulaye A, Ghellam M, Kpoclou YE, Aïssi MV. Tropical Almond Tree (Terminalia catappa L.): A Comprehensive Review of the Phytochemical Composition, Bioactivities and Economic Potential. Pharmaceuticals. 2026 Jan 5;19(1):99. https://doi.org/10.3390/ph19010099 PMid:41599698 PMCid:PMC12845074
25. Sene CF, McCann MC, Wilson RH, Grinter R. Fourier-transform Raman and Fourier-transform infrared spectroscopy (an investigation of five higher plant cell walls and their components). Plant physiology. 1994 Dec 1;106(4):1623-31. https://doi.org/10.1104/pp.106.4.1623 PMid:12232436 PMCid:PMC159706
26. Sahoo MR, Umashankara MS. FTIR based metabolomics profiling and fingerprinting of some medicinal plants: an attempt to develop an approach for quality control and standardization of herbal materials. Pharmacogn. Res. 2022;15:163-7. https://doi.org/10.5530/097484900288