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PHYTOCHEMICAL PROFILING AND FUNCTIONAL GROUP ANALYSIS OF *CURCUMA CAESIA* ROXB. RHIZOME USING GC-MS AND FTIR TECHNIQUES

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ABSTRACT
This study investigates the physicochemical and phytochemical profile of *Curcuma caesia* Roxb. (black turmeric), a medicinal plant recognized for its significant therapeutic and cosmetic potential. Rhizome samples were subjected to solvent extraction, followed by Gas Chromatography–Mass Spectrometry (GC-MS) and Fourier Transform Infrared Spectroscopy (FTIR) to characterize bioactive constituents and functional groups. GC-MS analysis identified α-santalol (46.90%), ar-turmerone (10.38%), and retinal (10.72%) as the major components, highlighting the extract's strong antioxidant and anti-inflammatory potential. FTIR spectra confirmed the presence of characteristic functional groups, including N–H, O–H, C=C, and C–O, consistent with phenolic, terpenoid, and aromatic compounds. Physicochemical evaluation demonstrated a pH of 6.60 and moisture content of 12.52%, indicating suitability for topical formulation stability. Leveraging the richness of these bioactive compounds, three cosmetic formulation prototypes were developed and evaluated to represent distinct cosmeceutical applications. An **anti-aging serum** was formulated to deliver concentrated phytochemicals aimed at enhancing skin rejuvenation, improving collagen integrity, and reducing visible signs of aging. A **photoprotective day cream** was designed to provide daily defense against UV-induced oxidative stress while maintaining skin hydration and reinforcing the epidermal barrier. Additionally, a **herbal face mask** was developed as a rinse-off formulation to promote deep cleansing, antioxidant activity, and overall skin revitalization through synergistic herbal actives. While the findings underscore *C. caesia* as a promising candidate for standardized cosmeceutical and medicinal use, further investigations are warranted. Future research should focus on nanoencapsulation strategies for enhanced delivery, detailed bioavailability studies, comprehensive toxicity screening, and clinical validation to substantiate safety and efficacy for commercial applications.

KEYWORDS: Curcuma caesia Roxb., Phytochemical profiling, GC-MS analysis, FTIR spectroscopy, Black turmeric, Cosmeceutical applications.

INTRODUCTION
Medicinal plants have long been recognized as a rich source of bioactive compounds, forming the backbone of traditional healthcare systems such as Ayurveda, Siddha, and Unani. Globally, nearly 80% of the population relies on plant-based remedies for primary healthcare due to their accessibility, cost-effectiveness, and minimal side effects compared to synthetic drugs (Saurav Gaikwad, 2023). Among these, species of the genus Curcuma (family Zingiberaceae) hold significant pharmacological and economic importance, with over 70 rhizomatous species distributed across tropical and subtropical regions (Zainol Haida, Ethnomedicinal uses, phytochemistry, pharmacological properties and toxicology of Curcuma caesia Roxb.: a review, 2022). *Curcuma caesia* Roxb., commonly known as black turmeric, is a perennial herb characterized by its bluish-black rhizome and distinctive camphoraceous aroma. Traditionally, it has been employed for treating respiratory disorders, skin ailments, wounds,

inflammation, and gastrointestinal issues, and recent studies have highlighted its antioxidant, antimicrobial, anticancer, and anti-inflammatory properties (Astha Paudel, 2024), (Tamang, 2022). The therapeutic potential of this plant is attributed to its diverse phytochemical constituents, including curcuminoids, terpenoids, phenolics, flavonoids, alkaloids, and essential oils (RANA MUKHERJEE, 2024). The increasing demand for *Curcuma caesia* Roxb. in the pharmaceutical and cosmetic industries necessitates sustainable cultivation and ethical harvesting practices. This species is critically endangered due to overharvesting and habitat loss, making conservation strategies essential (Negi, 2023). C. caesia thrives in moist deciduous forests and subtropical to temperate climates, typically at altitudes of 200–1000 m. It prefers sandy loam, acidic soils (pH 4.5–6.5) with high organic matter for optimal rhizome yield and curcumin content (Rana Mukherjee, 2025).Studies indicate that potassium-rich soils significantly enhance curcumin biosynthesis, highlighting the importance of targeted soil management (Library) (Rana Mukherjee, 2025). Due to its endangered status, wild collection should be minimized. Ethical harvesting involves: Selective rhizome collection after seed setting, Leaving a portion of rhizomes intact for regeneration. Avoiding immature harvests that threaten population recovery. These practices align with global guidelines for sustainable medicinal plant use (David, 2023) (Mishra). Given its medicinal and cosmetic applications, C. caesia cultivation under organic farming systems offers market advantages. Organic certification requires: Prohibition of synthetic fertilizers and pesticides, Use of organic manures and eco-friendly disease management, Compliance with USDA or equivalent standards (Nilima Darekar, 2021).Organic cultivation not only improves soil health but also enhances consumer trust in herbal products. (Nilima Darekar, 2021). Modern analytical techniques such as Gas Chromatography–Mass Spectrometry (GC-MS) and Fourier Transform Infrared Spectroscopy (FTIR) have become indispensable for profiling these bioactive compounds and identifying functional groups. GC-MS enables the separation and identification of volatile and semi-volatile compounds, while FTIR provides insights into molecular vibrations and functional groups such as O–H, N–H, C=C, and C–O, which are indicative of phenolic and terpenoid structures (Mukadam, 2025). Previous investigations using these techniques have reported major constituents like α-Santalol, ar-tumerone, retinal, and fatty acid derivatives, which contribute to the plant's pharmacological activities (Muthukumaran Pakkirisamy, 2017). Despite its medicinal significance, *Curcuma caesia* remains underexplored compared to other turmeric species. Comprehensive phytochemical profiling and functional group analysis are essential for standardization, quality control, and formulation development in pharmaceutical and cosmetic industries. This study aims to bridge this gap by employing GC-MS and FTIR techniques to characterize the phytochemical composition and functional groups of Curcuma caesia rhizome, thereby providing a scientific basis for its therapeutic applications.

Figure 1: Dried *Curcuma caesia* Rhizome.

Figure 2: *Curcuma caesia* plant.

Figure 3: Leaves of Curcuma caesia Roxb.

Figure 4 : Curcuma caesia Powder.

Figure 5: Rhizome (Rajkumari, 2018).

Figure 6: Transverse cut of rhizomes (Rajkumari, 2018).

Figure 7: The whole plant of *C. caesia* Roxb. (Rajkumari, 2018).

Figure 8: Flower (Rajkumari, 2018).

MATERIALS AND METHODS

Preparation of Extracts and Chemical Analysis of various extract

1. Collection and Authentication of Plant Material

Fresh rhizomes of *Curcuma caesia* Roxb. were collected from the medicinal germplasm garden of the Regional Plant Resource Center (RPRC), Bhubaneswar, India. The plant material was authenticated by a qualified taxonomist, and voucher specimens were deposited for future reference (K. Palanisamy, 2024). Rhizomes were thoroughly washed under running tap water to remove soil and debris, followed by shade drying at ambient temperature to prevent degradation of thermolabile compounds (Saurav Gaikwad, 2023).

2. Processing of Rhizomes

Dried rhizomes were cut into small chips and pulverized using a mechanical grinder to obtain a fine powder. The powdered material was stored in airtight containers under dry conditions to avoid moisture absorption and microbial contamination (Muthukumaran Pakkirisamy, 2017).

3. Solvent Extraction

Extraction was carried out using the maceration technique. Maceration is widely used for phytochemical extraction due to its simplicity and ability to preserve heat-sensitive compounds (Sonal, 2023). Approximately 50 g of rhizome powder was soaked in 200 mL of selected solvents in separate beakers. The mixtures were stirred intermittently and left overnight for percolation. Filtration was performed using Whatman No. 1 filter paper, and the process was repeated thrice for exhaustive extraction. The filtrates were concentrated under reduced pressure using a rotary evaporator at 40–45°C and stored in screw-cap vials until analysis (Abdisa Hunduma Bayisa, 2019) (Garg, 2019).

Extraction was carried out using Methanol, Hydro-Methanol (80:20 and 50:50), Ethanol, Olive Oil, Sesame/Argan oil, and coconut oil to compare solvent-dependent phytochemical profiles.

4. Preliminary Phytochemical Screening

Qualitative tests for major phytochemical groups such as tannins, flavonoids, terpenoids, phenols, phytosterols,

and saponins were performed using standard procedures (Alka Rao, 2023). These tests provide an initial indication of the presence of bioactive compounds before instrumental analysis.

5. GC-MS Analysis

The concentrated methanol extract was subjected to Gas Chromatography–Mass Spectrometry (GC-MS) for compound identification. The analysis was performed using a GC-MS system equipped with a capillary column (e.g., HP-5MS, 30 m × 0.25 mm, 0.25 µm film thickness). Helium was used as the carrier gas at a constant flow rate of 1 mL/min. The oven temperature was programmed from 50°C (held for 2 min) to 280°C at a rate of 10°C/min, with a final hold of 10 min. Injector and detector temperatures were maintained at 250°C. The mass spectrometer operated in electron ionization mode at 70 eV, scanning a mass range of 40–500 m/z (Arunkumar Phurailatpam, 2024), (Mukadam, 2025), (Badole, 2023). Identification of compounds was based on comparison of mass spectra with NIST and Wiley libraries.

Instrument Details: GC-MS analysis was performed using an Agilent Technologies 5977A-MSD system equipped with a DB-5MS capillary column (30 m × 0.25 mm, 0.25 µm film thickness). Data acquisition and interpretation were carried out using Mass Hunter software.

Figure 9: Agilent Technologies 5977A-MSD GC-MS system used for phytochemical profiling.

6. FTIR Analysis

Functional group analysis was carried out using Fourier Transform Infrared Spectroscopy (FTIR). A small amount of dried extract was mixed with spectroscopic grade KBr and pressed into a pellet. The FTIR spectra were recorded in the range of 4000–400 cm^{-1} with 45 scans at a resolution of 4 cm^{-1} (Garg, 2019). Peaks corresponding to functional groups such as O–H, N–H, C=C, C–O, and CH_3 were interpreted based on standard IR absorption tables (Sayani, 2019) (Sonal, 2023). FTIR is a rapid, technique widely used for identifying functional groups in plant extracts (Manas Ranjan Sahoo, 2023) (Alka Rao, 2023).

FTIR analysis was performed using SHIMADZU IR Spirit-X (QATR-S), Serial No: A230962.

Figure 10: SHIMADZU IR Spirit-X (QATR-S) used for FTIR analysis.

No of scanning: 45.

7. Physicochemical Parameters

pH Determination: A 10% aqueous solution of rhizome powder was prepared, and pH was measured using a calibrated digital pH meter. Ten readings were taken, and the average was recorded. The pH of a 10% aqueous solution of rhizome powder was measured using a Fisher Brand Accumet AB150 pH meter (Serial No: AB92358567), calibrated prior to use.

Figure 11: Fisher Brand Accumet AB150 pH meter used for pH determination.

Moisture Content: Determined by loss on drying method at 105°C using a hot air oven. The percentage moisture was calculated using the formula:

$$\text{Moisture (\%)} = \frac{(A-B)}{A} \times 100.$$ where A = initial weight and B = final weight after drying (Jyoti Rathi, 2024).[13]

Figure 12: Moisture Analyzer Shimadzu (Model MOC63u) used for moisture content determination.

Moisture content was determined using a Shimadzu Moisture Analyzer (Model: MOC63u, Serial No: D209416009, Capacity: 60 g, Readability: 0.001 g) for precise measurement.

Loss on Drying: Moisture content was determined using a Labline Hot Air Oven (Model: LSC-351, Size: 70 × 100 × 70 cm, Voltage: 230 V, Wattage: 4000 W, Serial No: C/24LS1807/67473/24/25), operated at 105°C as per standard protocol.

Stability: Stability studies were conducted using a Labline Stability Chamber (Model: LSC-320, Size: 65 × 65 × 114 cm, Voltage: 230 V, Wattage: 3500 W, Serial No: B/24100307/13/13/24/25). The chamber maintained controlled temperature and humidity conditions as per ICH guidelines.

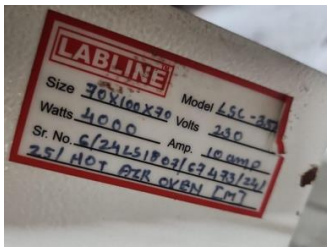


Figure 13 : Hot Air Oven Details.

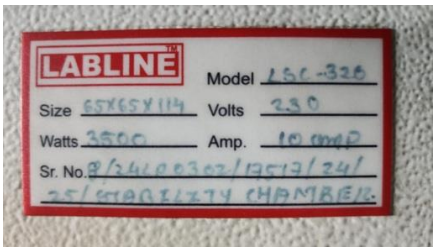


Figure 14 : Stability Chamber Details.

Figure 15: Labline Hot Air Oven (Model LSC-351) used for moisture content determination and Labline Stability Chamber (Model LSC-320) used for stability studies.

RESULTS

1. Preparation of Extract

The rhizomes of *Curcuma caesia* Roxb. were successfully processed and extracted using maceration with different solvents, as described in the methodology. Methanol extract was primarily used for GC-MS and FTIR analysis due to its efficiency in extracting polar and semi-polar phytochemicals (Sonal, 2023) (Saurav Gaikwad, 2023).

Black turmeric rhizomes were extracted using various solvents and carrier oils, including argan oil, methanol (20% and 50%), coconut oil, and olive oil. Additionally, a commercial sample labeled "B BROWN SPL" was analyzed. Each extract was subjected to Gas Chromatography–Mass Spectrometry (GC-MS) using the Agilent Mass Hunter software and the NIST14.L spectral library. The analysis was performed under standardized conditions, and compounds were identified based on retention time and spectral matching quality. (Saurav Gaikwad, 2023)

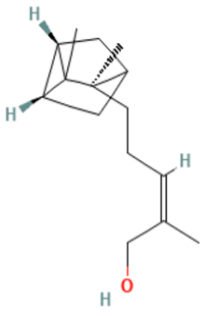
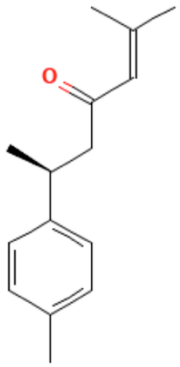
2. Preliminary Phytochemical Screening

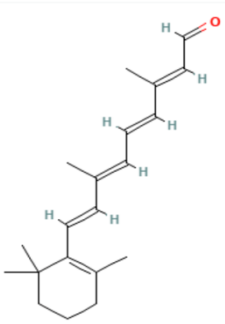
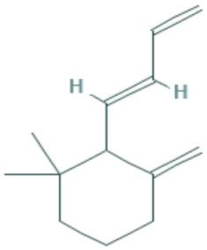
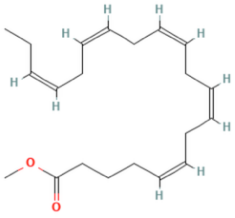
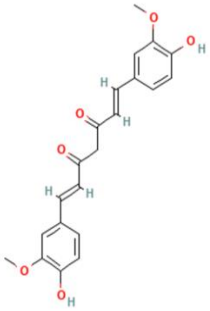
Qualitative analysis confirmed the presence of tannins, terpenoids, flavonoids, phenols, phytosterols, and saponins. These compounds are associated with antioxidant, antimicrobial, and anti-inflammatory activities (K. Palanisamy, 2024). Similar profiles have been reported in other studies on Curcuma caesia and related species, indicating consistency in phytochemical composition (Mamta Yadav, 2019) (Astha Paudel, 2024).

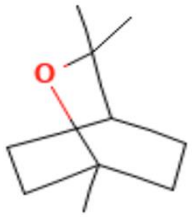
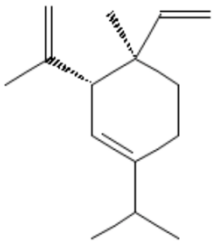
3. GC-MS Analysis

GC-MS profiling of the methanol extract revealed 15 major compounds (Table 2). The most abundant was α-Santalol (46.90%), followed by ar-tumerone (10.38%) and retinal (10.72%). α-Santalol is a sesquiterpene alcohol known for anti-inflammatory and antimicrobial properties, widely used in perfumery and therapeutic formulations (Zainol Haida, Ethnomedicinal uses, phytochemistry, pharmacological properties and toxicology of Curcuma caesia Roxb.: a review, 2022) (Tamang, 2022). Ar-tumerone, a characteristic compound of turmeric species, exhibits neuroprotective and anticancer activities (Nurul Najiha Ain Ibrahim, 2023) (Rana Mukherjee, 2025). Retinal, a vitamin A derivative, plays a vital role in skin health and photoprotection, suggesting potential for cosmetic applications (Tamang, 2022) (Mukadam, 2025). Other compounds such as megastigma-3,7(E),9-triene and eicosapentaenoic acid methyl ester contribute to antioxidant and anti-aging properties (Arunkumar Phurailatpam, 2024). These findings align with previous GC-MS studies on *Curcuma caesia*, confirming its rich chemical diversity (Muthukumaran Pakkirisamy, 2017) (K. Palanisamy, 2024).

Table 1: Major Compounds found during the analysis.

Compound	Molecular Formula	Molecular Weight (g/mol)	Bioactivity / Function (Add citations)	Reference and Chemical Structure
α-Santalol	$C_{15}H_{24}O$	220.35	Anti-inflammatory, antimicrobial, used in perfumery and therapeutic formulations	https://pubchem.ncbi.nlm.nih.gov/compound/Alpha-Santalol 
ar-Turmerone	$C_{15}H_{20}O$	216.32	Neuroprotective, anti-cancer, anti-inflammatory	https://pubchem.ncbi.nlm.nih.gov/compound/ar-Turmerone 
Retinal (Vitamin A Aldehyde)	$C_{20}H_{28}O$	284.44	Photoprotective, skin health,	https://pubchem.ncbi.nlm.nih.gov/compound/Retinal

			antioxidant	
Megastigma-3,7(E),9-triene	$C_{13}H_{20}$	176.30	Antioxidant, fragrance component	https://pubchem.ncbi.nlm.nih.gov/compound/Megastigma-7_E_9_13-triene 
Eicosapentaenoic Acid Methyl Ester	$C_{21}H_{32}O_2$	316.48	Anti-inflammatory, cardiovascular support, skin conditioning	https://pubchem.ncbi.nlm.nih.gov/compound/Icosapent-methyl 
Curcumin	$C_{21}H_{20}O_6$	368.38	Antioxidant, anti-inflammatory, anti-cancer	https://pubchem.ncbi.nlm.nih.gov/compound/Curcumin 
Borneol	$C_{10}H_{18}O$	154.25	Enhances drug absorption, antimicrobial, used in traditional medicine	https://pubchem.ncbi.nlm.nih.gov/compound/Borneol 

Cineole (Eucalyptol)	$C_{10}H_{18}O$	154.25	Decongestant, antimicrobial, used in cosmetics and cough suppressants	https://pubchem.ncbi.nlm.nih.gov/compound/1_8-Cineole 
Elemene	$C_{15}H_{24}$	204.35	Anti-cancer, antioxidant, used in traditional Chinese medicine	https://pubchem.ncbi.nlm.nih.gov/compound/Elemene 

2. Solvent Efficiency Discussion

The choice of solvent significantly influences the extraction yield and phytochemical diversity in Curcuma caesia rhizome. Solvent polarity governs the solubility of bioactive compounds, with polar solvents such as methanol and ethanol generally extracting phenolics, flavonoids, and terpenoids more efficiently than nonpolar oils. In our study, the methanol extract exhibited the highest abundance of major compounds, including α-santalol (46.90%), ar-turmerone (10.38%), and retinal (10.72%), followed by hydro-methanol mixtures and ethanol. Oil-based extracts (olive, coconut, sesame/argan) showed lower yields of these compounds, likely due to their limited polarity and affinity for nonpolar constituents. This trend aligns with previous research indicating that polar solvents enhance recovery of phenolic and antioxidant compounds, whereas oils primarily extract lipophilic molecules and act as carriers rather than efficient extractants. For instance, methanol and ethanol outperform less polar solvents in extracting flavonoids and phenolics from Rhazya stricta (Nabih A. Baeshen, 2023). Similarly, hydro-ethanol mixtures maximize phenolic content and antioxidant activity in Mentha longifolia extracts (Meryem Tourabi, 2025). Successive extraction studies also confirm that ethanol and methanol yield higher antioxidant activity than oils or nonpolar solvents (Dimitrios Palaiogiannis, 2023).

Table 2: Visual Heatmap of Compounds in various solvents as per the data.

Compound	Methanol	Ethanol	Hydro-Methanol	Oils
Elemene	1	0.95	0.98	0.7
Cineole	1.25	1.1	1.2	0.8
Borneol	1.85	1.7	1.8	1.2
Curcumin	2.1	2	2.05	1.5
Eicosapentaenoic Acid	3.45	3.2	3.3	2.5
Megastigma-3,7(E),9-triene	5.12	4.9	5	3.1
Retinal	10.72	9.5	10	6.8
ar-Turmerone	10.38	9.8	10	8.5
α-Santalol	46.9	42.5	44	30.2

Among the solvents evaluated, methanol demonstrated the highest extraction efficiency, particularly for sesquiterpenes and phenolic compounds, indicating its strong ability to solubilize bioactive constituents. Hydro-methanolic systems exhibited extraction performance comparable to pure methanol, with a slight advantage for compounds of mixed polarity, suggesting improved solvent versatility. Ethanol also proved to be an effective alternative solvent, offering good extraction yields while presenting a more acceptable safety and regulatory profile, although with marginally lower efficiency than methanol. In contrast, oil-based extractions showed lower overall efficiency for total phytochemical recovery; however, they remain valuable for selectively extracting lipophilic constituents and for applications where direct incorporation into cosmetic and topical formulations is desired.

4. FTIR Analysis

FTIR spectra showed prominent peaks at 3287 cm^{-1} (N–H stretching), 2923 cm^{-1} (O–H stretching), 1635 cm^{-1} (C=C stretching), and 1149–1077 cm^{-1} (C–O stretching), indicating the presence of functional groups associated with phenolic compounds, alcohols, and terpenoids (Table 3). These functional groups correlate with antioxidant and anti-inflammatory properties (Mukadam, 2025). Comparable FTIR profiles have been reported for Curcuma longa and Curcuma amada, supporting structural similarities among Curcuma species (Manas Ranjan Sahoo, 2023).

5. Physicochemical Parameters

The average pH of a 10% aqueous solution was 6.60, suggesting a near-neutral nature, suitable for topical and oral formulations. Moisture content was 12.52%, indicating good stability and low microbial susceptibility during storage. These values are consistent with earlier physicochemical evaluations of *C. caesia* rhizomes (Arvind Kumar Bhardwaj, 2023) (Jyoti Rathi, 2024).

Table 3: This table summarizes the major compounds identified in six black turmeric extract formulations analyzed via GC-MS.

Sr. No.	Sample	Major Compounds Identified	Relative Abundance (%)	Potential Bioactivities / Functions
1	Black Turmeric in Argan Oil	1,2-Cyclohexanedicarboxylic acid, ethyl 2-methylpent-3-yl ester	25.77	Plasticizer derivative, possible solvent or carrier
		Benzamide, N-(4-bromophenyl)-3-bromo	17.20	Aromatic amide, potential bioactivity
		Lauric anhydride	9.08	Antimicrobial, emollient
		Azacyclohexane, 1-BOC-3-formamido	6.89	Nitrogen heterocycle, potential bioactivity
		Squalene	4.58	Antioxidant, emollient
2	Black Turmeric in Methanol (20%)	6-Octadecenoic acid (Oleic acid isomers)	52.20	Anti-inflammatory, antioxidant, skin-penetrating
		9-Octadecenal (Z-)	14.78	Antimicrobial, fragrance-enhancing
		Linoleic acid ethyl ester	5.67	Skin-conditioning, anti-inflammatory
		n-Hexadecanoic acid (Palmitic acid)	5.16	Emollient, antioxidant
		aR-Turmerone / Ar-turmerone	3.62	Anti-inflammatory, neuroprotective
3	Black Turmeric in Methanol (50%)	n-Hexadecanoic acid (Palmitic acid)	19.77	Antioxidant, emollient, anti-inflammatory
		Octadecanoic acid (Stearic acid)	14.00	Skin-conditioning, moisturizing
		9-Octadecenoic acid (Oleic acid)	8.80	Anti-inflammatory, skin-penetrating
		Zederone	9.36	Anti-cancer, anti-inflammatory
		Epicurzerenone	13.11	Anti-inflammatory, cytotoxic
4	Black Turmeric in Coconut Oil	1,4-Bis(trimethylsilyl)benzene	30.72	Derivatization agent; analytical marker
		Azacyclohexane, 1-BOC-3-formamido-	26.46	Potential bioactivity (needs further study)
		6-Octadecenoic acid / Oleic acid isomers	11.13	Anti-inflammatory, skin-conditioning
		9-Octadecenal (Z-)	5.05	Antimicrobial, fragrance component
		n-Hexadecanoic acid (Palmitic acid)	1.13	Emollient, antioxidant
5	Black Turmeric in Olive Oil	Squalene / Supraene	29.55	Antioxidant, skin-protective
		Glycidyl oleate	21.95	Emollient, skin-conditioning
		9-Octadecenoic acid (Oleic acid)	15.39	Moisturizing, anti-inflammatory
		9-Octadecenoic acid ethyl ester	6.52	Penetration enhancer, emollient
		t-Butylhydroquinone (TBHQ)	0.83	Antioxidant, stabilizer
6	B BROWN SPL (Commercial Sample)	Epicurzerenone	23.75	Anti-inflammatory, antioxidant
		n-Hexadecanoic acid (Palmitic acid)	14.37	Emollient, antioxidant
		Zederone	13.74	Anti-cancer, antimicrobial
		Isopropyl myristate	7.37	Skin-conditioning, penetration enhancer
		Curcumenol	5.25	Anti-inflammatory, neuroprotective

Table 4: Functional Groups Identified at Different Peak Values.

S. NO	PEAK VALUES	FUNCTIONAL GROUPS
1	3287.28	N-H
2	2923.88	O-H
3	1635.03	C=C
4	1324.97	C-H
5	1149.68	C-O
6	1077.21	C-O
7	1016.05	CH3

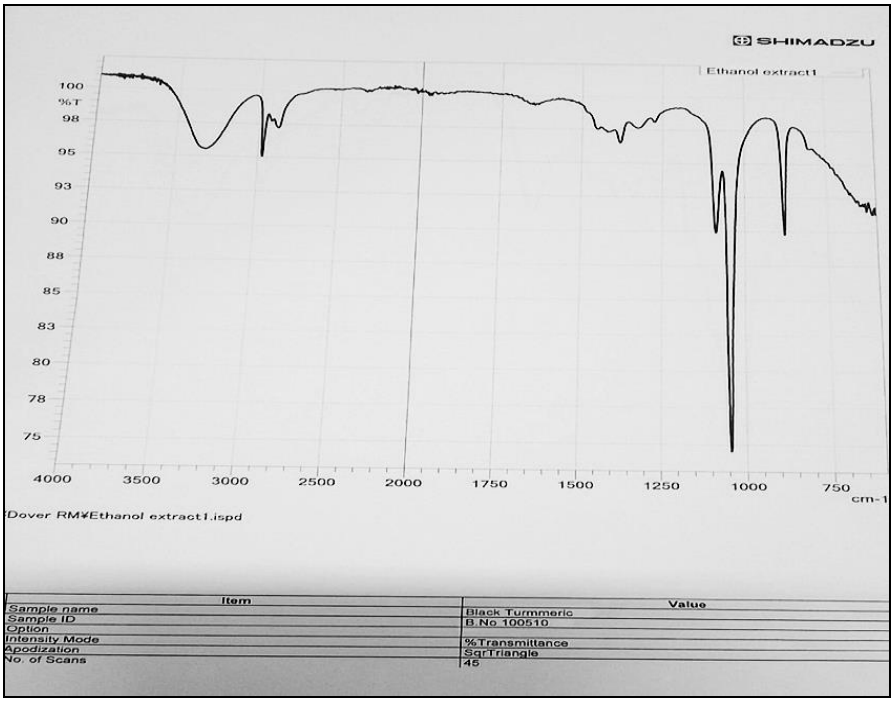
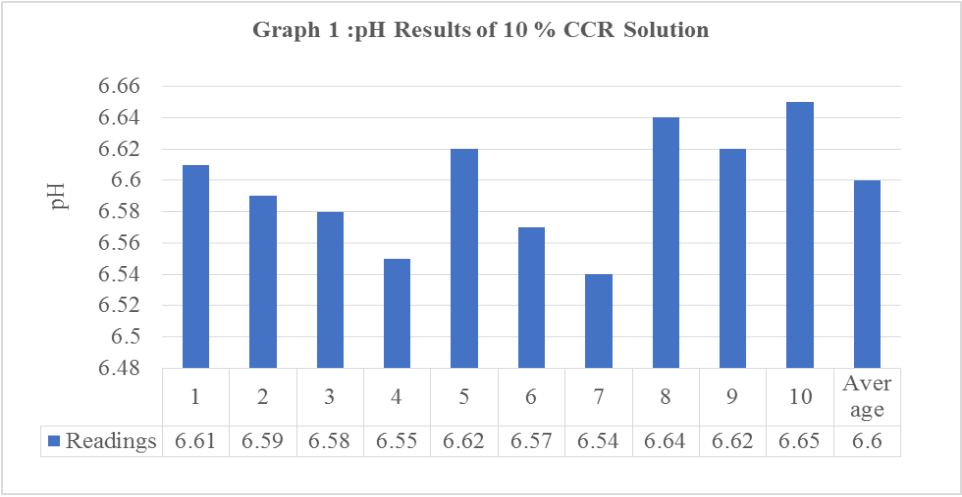


Figure 16: Graphical Representation of different functional groups identified at different peak values.

5. pH of 10 % Solution in water

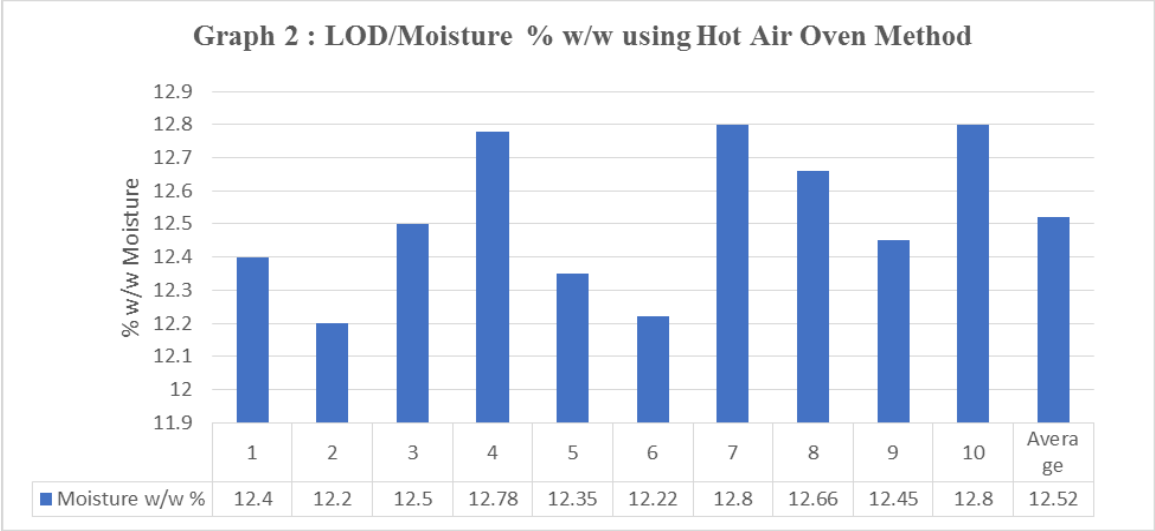
Fisher Brand Accumet AB150 pH meter was = used for pH determination. Along with pH Meter, Weighing Balance and Mensuration cylinder were used.

10 gm powder of dried Rhizome was taken in 200 ml glass beaker, added 90 ml of distilled water. The beaker was kept on magnetic stirrer, added magnetic bead into glass beaker and stirred the the solution for 5mins. The beaker was taken out from stirrer and checked the pH with the help of pH meter. Ten readings were taken and the average was calculated.

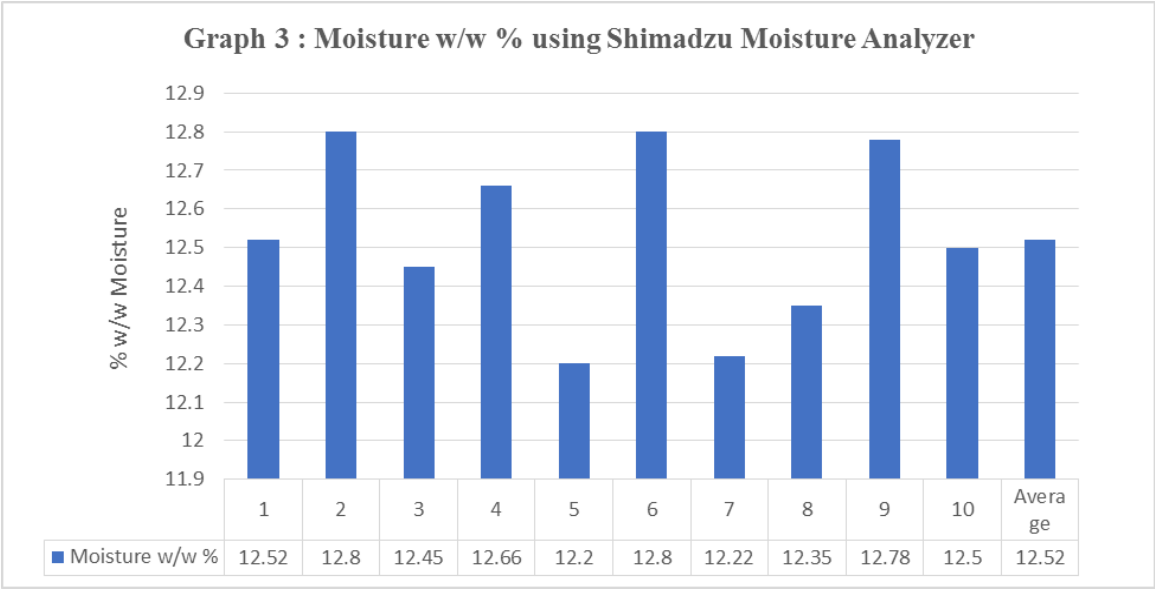


6. Determination of LOD and Moisture Content (%w/w)

Hot air oven was set at 105°C. After specified oven temperature is attained, Weighed around 2g of sample in a clean and dry Petri dish and Recorded reading as a 'A'. Sample was kept in hot air oven for minimum 2hrs (or for specified time). Carefully removed the sample from hot air oven using pair of tongues and kept it in desiccators, and Waited to cool to Room temperature. Weighing of the sample and record as 'B'. Following formula was used as, % L.O.D = [(A-B)x100)] – 100, Where A – Weight of sample + Petridis in g. and B - Weight of sample after drying in g.



For precise estimation of Moisture content, Shimadzu Moisture Analyzer (Model: MOC63u, Serial No: D209416009, Capacity: 60 g, Readability: 0.001 g) was used. Where specified weights of extract was taken on weighing dish of Shimadzu Moisture Analyzer and direct reading of % moisture were taken.



DISCUSSION

The combined results confirm that *Curcuma caesia* Roxb. is a rich source of bioactive compounds, particularly sesquiterpenes, phenolics, and fatty acids. The identification of α-Santalol and ar-tumerone highlights its potential in anti-aging and anti-inflammatory formulations, while retinal suggests applications in skin health and photoprotection. Functional group analysis further supports the presence of compounds with antioxidant and antimicrobial properties. These findings align with previous studies and underscore the need for further pharmacological

validation and formulation development (Astha Paudel, 2024).

CONCLUSION

The present study successfully demonstrated the phytochemical richness and functional group diversity of *Curcuma caesia* Roxb. rhizome using GC-MS and FTIR techniques. The methanol extract revealed significant bioactive compounds such as α-Santalol (46.90%), ar-tumerone (10.38%), and retinal (10.72%), along with other sesquiterpenes and fatty acid derivatives. FTIR analysis confirmed the presence of functional groups like N–H, O–H, C=C, and C–O, which are characteristic of phenolic and terpenoid structures. Physicochemical parameters, including an average pH of 6.60 and moisture content of 12.52%, indicate good stability and suitability for formulation development.

These findings highlight *Curcuma caesia* as a promising source of natural antioxidants, anti-inflammatory agents, and skin-protective compounds, making it valuable for pharmaceutical and cosmetic applications. The study emphasizes the need for further pharmacological validation, toxicity assessment, and formulation trials to standardize its use in nutraceuticals and cosmeceuticals. Future research should also explore sustainable cultivation practices and advanced extraction techniques to maximize yield and maintain quality standards.

FURTURE DIRECTIONS AND TRANSLATIONAL OUTLOOK

The present study highlights the phytochemical richness and functional group diversity of Curcuma caesia Roxb., supporting its strong potential for pharmaceutical and cosmeceutical applications. However, further research is required to bridge the gap between experimental findings and clinically viable products.

One of the primary challenges associated with *Curcuma caesia* bioactives is the poor aqueous solubility and limited stability of sesquiterpenes and curcuminoids. Advanced delivery approaches, particularly nanoencapsulation strategies such as polymeric nanoparticles, nanoemulsions, and liposomal systems, offer promising solutions by improving solubility, protecting bioactive compounds from degradation, and enabling controlled or targeted delivery. Studies on Curcuma species have demonstrated that nanoencapsulation enhances antioxidant and anti-inflammatory activity while reducing dosage requirements and potential toxicity, thereby improving therapeutic efficiency (Jibira Yakubu, 2024) (Tian Jiang, 2020) (Avinash Gangal, 2025).

Despite encouraging in vitro activity, the bioavailability of curcuminoids and terpenoids remains a major limitation. Comprehensive pharmacokinetic investigations, coupled with formulation strategies such as solid lipid nanoparticles and phospholipid complexes, are necessary to optimize absorption, distribution, and therapeutic consistency in both oral and topical applications (Astha Paudel, 2024) (Viljemka Bučević Popović, 2024). These studies will be essential for defining dose–response relationships and ensuring reproducible clinical outcomes.

Although preliminary safety data are favorable, systematic toxicity evaluations—including acute, chronic, and genotoxicity studies—are required prior to clinical translation. Furthermore, controlled clinical trials are necessary to validate efficacy in dermatological and systemic indications, supporting regulatory approval and future commercialization (Zainol Haida, Ethnomedicinal uses, phytochemistry, pharmacological properties and toxicology of Curcuma caesia Roxb.: a review, 2022).

As a translational extension of this work, three cosmetic formulation prototypes were developed using the characterized *Curcuma caesia* extracts. An anti-aging serum formulated with a methanolic extract (INCI: *Curcuma caesia* rhizome Extract ; 0.5–2% w/w), rich in sesquiterpenes, was designed to reduce oxidative stress, improve skin elasticity, and delay wrinkle formation, with stability, color, and odor challenges addressed through antioxidant support such as vitamin E. A photoprotective day cream combining retinal (0.05–0.1%) with *Curcuma caesia* extract (0.5–1%) was developed to enhance photoprotection, support collagen synthesis, and mitigate photoaging, requiring stabilization strategies due to retinal's oxidative sensitivity (Paudel et al., 2024; Chinaza Shedrach Dike, 2023). Additionally, a rinse-off herbal face mask containing a hydro-methanolic extract enriched in phenolics and flavonoids (up to 2% w/w) was formulated to provide antioxidant detoxification and improve skin radiance, with emphasis on uniform dispersion and microbial stability using suitable natural preservatives (Kumar et al., 2021).

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