



GARCINIA CAMBOGIA RIND OIL AS A POTENTIAL BIO-BASED PRECURSOR: EXTRACTION, CHARACTERIZATION, AND EPOXIDATION FEASIBILITY

Ravikiran¹
Shreyas G Kashyap
Ravikumar Beeranur
Rupesh S
Ganesh Arjun S
Yathik Aiyappa S C

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A B S T R A C T

With the rise of renewable resources as an engineering material, vegetable oil have been investigated as a resource for chemically functional molecules. There are variety of structures in vegetable oils which consist of fatty acids and other oxygen-containing ingredients that are enough to be chemically modified to add functional groups that could be used in material development. In this study *Garcinia cambogia* pericarp (rind) oil was studied from the chemical-structure and precursor-feasibility point of view. The extracted oil was analyzed in terms of chemical composition by Gas Chromatography–Mass Spectrometry (GC–MS) to determine its major constituents and chemically reactive functionalities. The oil was then treated with the in-situ peracetic acid system. The structural features of the untreated and chemically modified oils were compared using Fourier Transform Infrared (FTIR) spectroscopic analysis. GC–MS analysis showed that the composition of the material is chemically heterogeneous, with the presence of compounds related to fatty acids (3.18% relative peak area), short-chain organic acids (propanoic acid, 27.24% area), and oxygenated furan derivative (32.63% area). The results show the raw chemical properties and epoxidation response of *Garcinia cambogia* oil, evidenced by the marked reduction of the alkene unsaturation band at 1631.95 cm^{-1} and the emergence of new oxirane ring absorption bands at 908.91 cm^{-1} and 835.08 cm^{-1} . Because physical and mechanical application performance properties were not evaluated in this study, the present findings establish qualitative spectroscopic evidence of oxirane ring introduction rather than demonstrated engineering utility. The resulting epoxide functionality represents a prospective pathway for future empirical evaluation in bio-based polymers, coatings, thermoset resins, and composite materials.



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¹ Corresponding author: Ravikiran
Email: nayak.ravikiran@gmail.com

1. INTRODUCTION

With the growing adoption of sustainability in engineering, renewable materials have been developed as alternatives to the standard petroleum-based materials. Vegetable oils have been studied extensively due to the presence of ester groups in their molecules, hydrocarbon chains and the presence of varying degrees of unsaturation which can be used in chemical modification. Vegetable oils have a few possibilities for functionalization due to their chemical structure. The naturally occurring fatty-acid-based structures can be reacted at functional groups, including carbon–carbon double bonds, to introduce additional functionality into the molecules without destroying a significant amount of the original renewable molecular structure. This has been applied in the preparation of vegetable oil-based polymers and other bio-based engineering materials. (Jašek & Figalla, 2025)

The epoxidation is one of these modification routes that is especially significant, since carbon–carbon double bonds can be converted to three-membered oxirane rings. The epoxy functionality that is generated creates a chemically active site for subsequent reactions, such as polymerisation, crosslinking and others. Research on epoxidized vegetable oils has shown that apart from its traditional application in lubricant development, the epoxide groups can also be employed in thermosetting materials, coatings and composite systems. The chemical modification of vegetable oil is therefore not only a chemical composition but also a functionalization of the original vegetable oil molecules, which makes the oils highly relevant to the field of engineering. Bio-based epoxy systems, thermosets and composites have been investigated using epoxidized vegetable oils. Their incorporation has been linked to the modification of the mechanical and thermomechanical properties, thus showing that chemical modification can be a pathway to obtain functional material precursors from renewable oils. (Miao, Wang, Su, & Zhang, 2014) In this context, *Garcinia cambogia* is a fascinating, but relatively understudied renewable resource. *Garcinia gummi-gutta* has been studied in terms of its phytochemical properties, seed properties, fatty-acid composition and other applications.

Despite the fact that many vegetable oils have been investigated, however, relatively few studies have been carried out on the chemical functionalization of *Garcinia* oil and its understanding of how the molecular properties can assist in the creation of materials. Thus, it is important to first determine the chemical composition of an unconventional oil before chemical modification is considered. GC–MS can be used to give information on the constituents of a complex oil and can help identify compounds derived from fatty acids as well as other chemically relevant compounds. (Priya Rani, Gokul Raj, & Bahuleyan Rameshkumar, 2022) The approach of GC–MS–based analysis has been extensively adopted for the analysis of fatty-acid composition and chemical

profile of vegetable oils. Unsaturated constituents are especially significant in the context of epoxidation, since the major sites of reaction that lead to the formation of oxirane are the carbon–carbon double bonds.

The epoxidation of vegetable oils with various catalytic and peracid systems has been proved in several studies. One of the methods already known for modification of the structures of unsaturated vegetable oils is the use of in-situ peracetic acid. After chemical modification, FTIR spectroscopy is a convenient way of monitoring changes in molecular functionality. Epoxidation reaction induced structural transformation can be assessed by the change in characteristic absorption due to unsaturation and presence of oxirane related absorption bands. (Mustapha et al., 2014) FTIR has been applied to track oxirane changes and iodine value changes during the vegetable-oil epoxidation process. Epoxidized vegetable oils have been extensively studied as renewable chemicals but most of the reported work is based on the well-known oils of soybeans, castor, canola, and other conventional oils. (Wagner, Luther, & Mang, 2001) The potential of using *Garcinia cambogia* oil as a source of chemically functionalized molecules is thus an opportunity to explore an unconventional renewable feedstock from an engineering-material perspective. (Malburet et al., 2020) The aim of this work is not, therefore, to determine the mechanical performance or suitability for application of the *Garcinia cambogia* oil but to determine its chemical characteristics and to demonstrate whether it is chemically possible to modify its molecular structure by epoxidation.

The study includes three main steps: (i) characterization of the untreated oil using GC–MS, (ii) in situ peracetic acid epoxidation of the oil, and (iii) comparison of the untreated and epoxidated oils by FTIR. The structural information obtained is then discussed in terms of potential future uses of the materials in engineering, such as polymeric, coating, composite and thermomechanical studies.

2. MATERIALS AND METHODS

The overall experimental methodology and roadmap for the extraction, GC–MS characterization, and in-situ peracetic acid epoxidation of *Garcinia cambogia* rind oil is depicted in Figure 1.



Figure 1. Experimental workflow of the study

2.1 Extraction of Raw Garcinia Oil

In this study, the *Garcinia cambogia* pericarp lipophilic extract (rind oil) was extracted using a traditional solvent-free method of thermal aqueous extraction as shown in Figure 2. The fresh *Garcinia cambogia* fruits were sourced from local villages in Kerala, India, and were first examined and cleaned to get rid of any extraneous material. The pulp was removed from the rind by hand and then the rind was washed to remove any pulp on the outside. The cleaned rind was shade-dried at ambient temperature, until it was free of moisture. The dried rind material was then thermally extracted in a stainless-steel vessel containing water at about 80-90 °C for about 1 hour following traditional Indian household processing techniques (Kudampuli aqueous boiling method). During this stage there was no organic solvent or other extraction chemical added. The rind was heated and the oil layer floating on the water surface was then gathered from the surface, decanted, gently warmed at low heat to remove residual surface moisture, and filtered to remove suspended particulate material. The oil that was extracted was then placed in clean, dry containers, that were airtight and amber coloured, until further analysis. The route for extraction was chosen so that the oil could be extracted without adding other chemicals to the mix from the solvents used, which might make the subsequent chemical characterisation of the oil more difficult (Priya Rani et al., 2022).



Figure 2. Thermal extraction of *Garcinia cambogia* rind oil

Further modification of the extracted material is warranted as evidenced by previous investigations which showed the presence of chemically diverse lipid resources in the *Garcinia* species (Patil et al., 2016). The extracted product is described as a "rind oil" or "pericarp lipophilic extract" because it forms a viscous hydrophobic liquid phase at ambient conditions, distinguishing it from solid triglyceride seed fats (Kokum butter) obtained from *Garcinia* seeds.

2.2 GC–MS Characterization

The extracted *Garcinia cambogia* rind oil was characterized using Gas Chromatography–Mass Spectrometry (GC–MS) at the Biofuel Regional Quality Testing Laboratory (BRQAL), GKVK, Bengaluru (Sample ID: BRQAL-2025-26-075(1)) as shown in Figure 3.



Figure 3. GC–MS system used for chemical characterization

Prior to injection, the rind oil sample (1.0 µL injection volume) was prepared by dissolving in analytical-grade solvent without chemical derivatization (Guerrero-Esperanza et al., 2023). Chromatographic separation was performed using helium as the carrier gas under a temperature-programmed run over a 40-min Total Ion Chromatogram (TIC) acquisition time. The aim of the analysis was to determine the chemical composition of the raw oil and to select constituents which had chemically relevant functional groups for bio-based processing. The 21 chromatographic peaks in the TIC were identified by comparing their mass spectra (fragmentation patterns and base peaks) with the reference NIST/WILEY spectral library that was stored in the GCMS solution software instrument. Results were then classified by main chemical classes of the compounds identified. Special consideration was paid to compounds which were linked with unsaturated structures such as 6-octadecenoic acid ((Z)-, 2.10% peak area at R.Time 24.45 min) and 13-docosenamide ((Z)-, 1.71% peak area at R.Time 36.29 min), since carbon–carbon double bonds are the potential reaction sites for

epoxidation. The subsequent FTIR results were then interpreted based on the chemical information obtained from the GC–MS results.

2.3 Epoxidation of Vegetable Oils

The peracid-based oxidation systems have been extensively studied for the epoxidation of vegetable oils due to the presence of reactive sites (carbon–carbon double bonds) in the unsaturated fatty acid chains. Epoxidation of different vegetable oils has been performed using hydrogen peroxide in the presence of organic acids and also in the presence of heterogeneous acid catalysts. (Danov et al., 2017) The epoxidation of castor oil has been carried out with hydrogen peroxide and acid ion-exchange resin catalysts and analogous catalytic methods have been reported for canola oil. Hydrogen peroxide in water with inorganic acids have also been used for cottonseed oil. Epoxidation of jatropha oil has been carried out with the peroxyacetic acid and peroxyformic acid systems and the hydrogen peroxide system has been studied for epoxidation of mahua oil. (Wai et al., 2019) Several other studies have shown the epoxidation of neem, sunflower and waste cooking oils with similar oxidation systems. The results from these studies showed that the reaction conditions and epoxidation behaviour were closely related with the fatty-acid composition and unsaturation degree of the individual feedstock. The approaches reported in the literature were used as a basis for the present study, which uses an in-situ peracetic acid system produced from hydrogen peroxide and acetic acid, with the addition of sulfuric acid. (Goud, Patwardhan, & Pradhan, 2006) The currently followed route was used as a basis to compare the structural change of *Garcinia cambogia* oil with epoxidation behaviour of other vegetable-oil feedstocks. The following FTIR analysis was thus conducted to see if the structural changes associated with the epoxidation process were also present in the present oil.

2.4 Epoxidation Procedure

The in-situ peracetic acid epoxidation reaction scheme converting double bonds into oxirane rings is depicted in Figure 4. In-situ peracetic acid epoxidation system was used for the chemical modification of the *Garcinia cambogia* oil. The method was chosen because peracid-based epoxidation is already a well-known method to convert carbon–carbon double bonds of vegetable oils to oxirane groups. Similar reaction systems have been shown to epoxidize canola, jatropha, and cottonseed, soybean and other vegetable oils in previous investigations. (Okieimen, Pavithran, & Bakare, 2005) In the present experiment, 10 mL of *Garcinia cambogia* oil was added into a beaker and stirred at around 300–400 rpm. The magnetic stirrer was used to heat the oil to 55–60 °C. The oxidizing mixture was prepared on a defined volumetric basis combining 10 mL of 30% (v/v) aqueous hydrogen peroxide with 3 mL of glacial acetic acid

(99.5% v/v) and 2 drops (~0.1 mL) of concentrated sulfuric acid (98% wt/wt) as catalyst, establishing a reactant volumetric ratio of 10:3:10 (oil:glacial acetic acid:30% H₂O₂). The oxidizing mixture was then added dropwise to the heated oil over about 10–15 min keeping the reaction temperature at 55–60 °C. After the completion of the addition, the reaction mixture was stirred for 3 h at 55–60 °C. The reaction was then cooled down to room temperature. The modified reaction mixture was extracted with diethyl ether, and the separated organic phase was purified by sequential washing with distilled water, 5% (w/v) aqueous sodium bicarbonate solution to neutralize residual acid, and distilled water. The organic phase was dried over anhydrous sodium sulfate, filtered, and the solvent was removed under reduced pressure at 40 °C using a rotary evaporator to isolate the solvent-free epoxidized oil product prior to FTIR analysis. The purpose of the present investigation was to find out whether epoxidation took place or not and not to optimize the epoxidation process. The experimental conditions were thus fixed for structural comparison, where physical product recovery (gravimetric mass yield of isolated epoxidized oil relative to starting oil) was distinguished from chemical conversion efficiency (qualitative oxirane formation evaluated via FTIR). A single, fixed reaction trial was intentionally conducted as an initial proof-of-concept feasibility screening experiment. While the raw plant material was extracted across pooled batches, conduct of a single reaction run means that inter-trial process variance was not evaluated, representing a recognized scope limitation of this qualitative feasibility study.

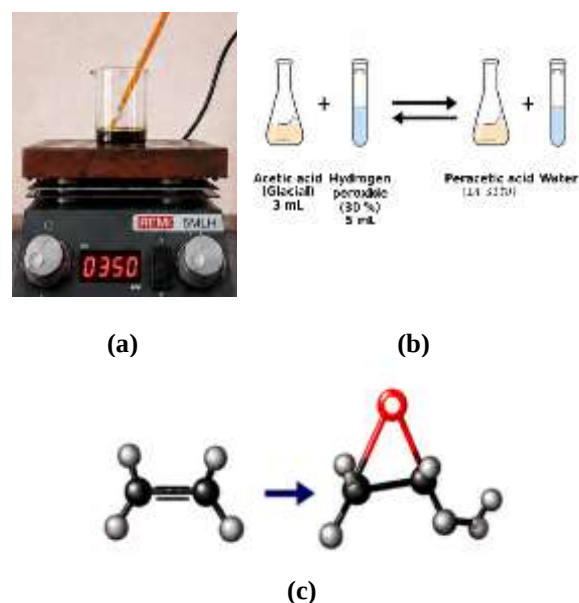


Figure 4. Schematic representation of the experimental epoxidation process: (a) experimental reaction setup with continuous heating and stirring, (b) formation of peracetic acid from acetic acid and hydrogen peroxide, and (c) conversion of a carbon–carbon double bond into an oxirane

2.5 FTIR Analysis

FTIR spectroscopy was used to study the changes in the structure of the untreated and epoxidized *Garcinia cambogia* oil using a PerkinElmer Spectrum II FTIR spectrometer equipped with an Attenuated Total Reflectance (ATR) sampling accessory as shown in Figure 5.



Figure 5. ATR-FTIR spectrometer used for structural analysis

Spectra for both neat liquid samples were recorded in ATR mode across the wave number range of $4000\text{--}400\text{ cm}^{-1}$ at a spectral resolution of 4 cm^{-1} with 16 co-added scans, following background spectrum calibration under ambient laboratory conditions. To ensure analytical instrument reproducibility, repeated instrumental measurement acquisitions (triplicate ATR-FTIR spectral scans and replicate GC-MS chromatographic injections) were performed on the same isolated sample phases. Peak locations and relative area percentages were averaged across repeated measurement scans to verify spectral band stability (within $\pm 0.5\text{ cm}^{-1}$). Analysis was concentrated on the characteristic's absorption areas of

hydroxyl, carbonyl and unsaturated functionalities in the untreated oil, and the emergence of the absorption areas of oxirane functionality after the chemical modification. (McNutt & He, 2016). The interpretation was done, mainly by comparison, between the untreated and epoxidized spectra. A decrease in the absorption due to carbon-carbon unsaturation and the presence of characteristic oxirane bands were interpreted as structural changes. (Salimon, Salih, & Yousif, 2010) Monitors of epoxidation and changes in oxirane functionality of vegetable oils have been performed by similar FTIR methodology.

3. RESULTS AND DISCUSSION

3.1 Chemical Characterization of *Garcinia cambogia* Oil by GC-MS

In this experiment, the chemical composition of *Garcinia cambogia* oil pericarp lipophilic extract) was identified by gas chromatography-mass spectrometry (GC-MS). The untreated *Garcinia cambogia* oil's chromatogram is shown in Figure 6. The chromatographic profile shows that the desired product from the extraction process is not just one predominant molecular species, but chemically heterogeneous. The compounds identified were fatty-acid derivatives as well as oxygen-containing compounds from various chemical classes (organic acids, furans, and oxygenated esters). The results of the chromatographic analysis are summarized in relative peak area percentages (TIC area %) as shown in Table 1. It is important to emphasize that relative peak-area percentages reflect chromatographic detector response and volatile constituents resolved under GC-MS conditions; they should not be treated as exact mass fractions (wt%) or as a direct quantitative measure of non-volatile bulk triglyceride content (Miao et al., 2014).

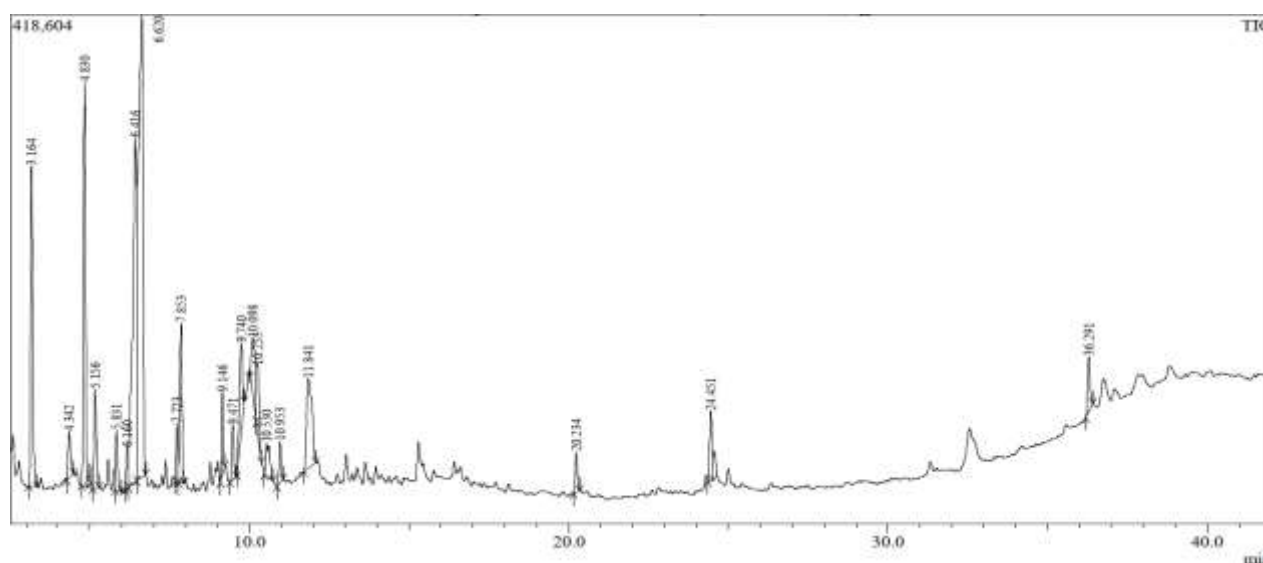


Figure 6. Chromatographic profile of *Garcinia Cambogia* Oil

Table 1. Identified compounds and their relative peak areas and retention times

No .	R.Time	I.Time	F. time	Area	Area%	Height %	Compound Name
1	3.164	3.080	3.345	1184011	8.20	11.98	Furfural
2	4.342	4.270	4.490	214032	1.48	1.71	2(5H)-Furanone
3	4.830	4.730	4.940	1444227	10.00	15.09	2,5-Furandione, 3-methyl-
4	5.156	5.080	5.280	380718	2.64	3.69	2-Furancarboxaldehyde, 5-methyl-
5	5.831	5.785	5.985	213163	1.48	2.24	Oxazolidine, 2,2-diethyl-3-methyl-
6	6.160	6.085	6.195	147520	1.02	1.50	Succinic anhydride
7	6.416	6.195	6.465	2425493	16.80	12.87	2,5-Furandione, dihydro-3-methylene-
8	6.620	6.465	6.745	3932212	27.24	17.27	Propanoic acid
9	7.723	7.645	7.770	184497	1.28	2.19	Levoglucosenone
10	7.853	7.770	7.945	608893	4.22	5.99	3-Pentenoic acid, 3-ethyl-, methyl ester
11	9.146	9.075	9.225	251880	1.74	3.10	N-[Carboxymethyl]maleamic acid dimethyl ester
12	9.471	9.385	9.590	219758	1.52	2.04	Piperidine, 1-nitroso-
13	9.740	9.605	9.830	518380	3.59	3.28	1H-Pyrazole-3-carboxylic acid, 2,5-dihydro-5-oxo-
14	10.098	10.005	10.210	443231	3.07	2.08	2,3-Trimethylene-4-pyrone
15	10.255	10.210	10.370	305577	2.12	2.54	Cyclopentanecarboxylic acid, 2-oxo-, ethyl ester
16	10.530	10.460	10.730	240015	1.66	1.26	Butanedioic acid, monomethyl ester
17	10.953	10.865	11.050	162954	1.13	1.58	Mono(2-ethylhexyl) phthalate
18	11.841	11.705	12.080	853187	5.91	3.36	1-Methyl -1,2,3-triazole-4-carboxylic acid
19	20.234	20.150	20.340	155531	1.08	1.50	n-Hexadecanoic acid
20	24.451	24.355	24.525	303688	2.10	2.63	6-Octadecenoic acid, (Z)-
21	36.291	36.200	36.425	246196	1.71	2.09	13-Docosenamide, (Z)-
				14435163	100.00	100.00	

R.Time = Retention Time; I.Time = Initial Time; F.Time = Final Time; Area(%) = Relative Peak Area; Height(%) = Relative Peak Height

The presence of unsaturated compounds (such as 6-octadecenoic acid, 2.10% area at R.Time 24.45 min, and 13-docosenamide, 1.71% area at R.Time 36.29 min) is especially important because carbon-carbon double bonds are chemically reactive sites which can undergo epoxidation (Goud et al., 2006). Thus, the GC-MS analysis gave the initial structural information for investigation of the possibility of chemically functionalizing extracted oil. The chemical diversity observed herein is also of significance for an engineering-material point of view. Renewable oils are not always homogenous feedstocks, and minor components within the oil could have an impact on the overall reactivity and hence the behaviour of the oil after reaction. The GC-MS profile therefore sets a precedent that the obtained *Garcinia cambogia* oil has a variety of constituents that are chemically different, including structures that could provide potential points to be functionalized. The compound distribution detected in the present sample characterized by a substantial proportion of short-chain organic acids (propanoic acid, 27.24% area) and furan/furanone derivatives (32.63% area) alongside fatty acyl species (3.18% area) which directly reflects the pericarp (rind) tissue origin and thermal aqueous extraction route, which liberates polar non-triglyceride lipophilic metabolites (Priya Rani et al., 2022). This also agrees with the general trend that *Garcinia* resources are chemically diverse, both in terms of lipids and non-lipids (Patil et al., 2016). The compositional changes of *Garcinia* oils and pericarp extracts have been previously reported in the related materials (Priya Rani et al., 2022).

3.2 Chemical Significance of the GC-MS Profile

The GC-MS Profile is useful for chemical characterization of the plant species. All the data obtained

by the GC-MS helps to understand the behaviour of the oil in chemical modification. Table 2 represents the significance of the various chemical compound classes identified through GC-MS analysis in various Engineering utilizations based on the compound compositions. The fatty-acid derived constituents (3.18% relative peak area) are identified, meaning that the presence of molecular structures with hydrocarbon chains and in part unsaturation is indicated. The relevance of these structural features is in the potential to change them to unsaturated sites, which can be epoxidized. Other oxygen containing compounds (including propanoic acid at 27.24% peak area and furan/furanone derivatives at 32.63% peak area) are present, suggesting that the extracted oil is not just a collection of "idealized triglyceride structures" typically associated with commercial seed oils. Rather, it has various chemical functional groups which could provide it with a variety of intermolecular interactions and polarities. A chemical diversity is important on an engineering perspective as the response of a renewable feedstock to chemical modification depends on the molecular structure. The goal is not just to find out whether there are any fatty acids in the oil, but whether the structure of the oil offers any chemically accessible sites where new functionality can be added. The unsaturated compounds detected by GC-MS in present study were used as the chemical basis to proceed with the epoxidation. The following FTIR analysis was then performed to ascertain whether or not the desired structural change was achieved. So, the role of GC-MS and FTIR are complementary: One is used to determine the chemical constituents present and the other is used to determine the chemical change induced by the chemical modification.

Table 2. Compounds & their Significance

Chemical class	Relative composition (%)	Engineering significance
Fatty acids	3.18	Provide reactive carbon–carbon double bonds suitable for epoxidation and contribute to boundary lubrication.
Esters	10.87	Improve lubricity, biodegradability and compatibility with lubricant formulations.
Amides	1.71	Polar compounds that may enhance surface adsorption and lubricating film formation.
Other polar compounds	13.52	Increase overall chemical reactivity and influence intermolecular interactions.
Organic acids	27.24	Increase feedstock polarity and may influence purification behaviour.
Aldehydes	10.84	Oxygen-containing constituents indicating chemical heterogeneity of the extracted rind oil.
Furans and other oxygenated compounds	32.63	May influence emulsion stability and downstream product recovery during purification.
Total	100.00	Oil exhibits a chemically heterogeneous composition suitable for feasibility assessment.

3.3 FTIR Characterization of the Untreated Oil

A number of characteristic absorption bands were detected and the untreated *Garcinia cambogia* oil FTIR spectrum is displayed in Figure. 7. A wide absorption band at 3370.72 cm^{-1} was found and this band could be related to O–H stretching vibrations of hydrogen-bonded hydroxyl groups in polar organic acids and trace moisture. This band is in agreement with the presence of oxygen containing constituents detected in the GC–MS analysis. A well-resolved band was identified at 1720.99 cm^{-1} and is linked to the carbonyl (C=O) stretching mode which is found in ester and fatty acid derivatives. This band represents an important clue as to the presence of the carbonyl-bearing molecular framework present in the untreated oil. An absorption at 1631.95 cm^{-1} was also observed. This is the area where carbon–carbon (C=C) unsaturation was observed to be present and it is especially significant in the current study as it is the site where the reaction is observed to occur during the epoxidation process. The FTIR results are thus consistent with the GC–MS results. The GC–MS analysis revealed the presence of unsaturated and oxygen containing components and FTIR spectrum showed proof of functional groups in the bulk sample. The results of the chemical modification were confirmed by FTIR.

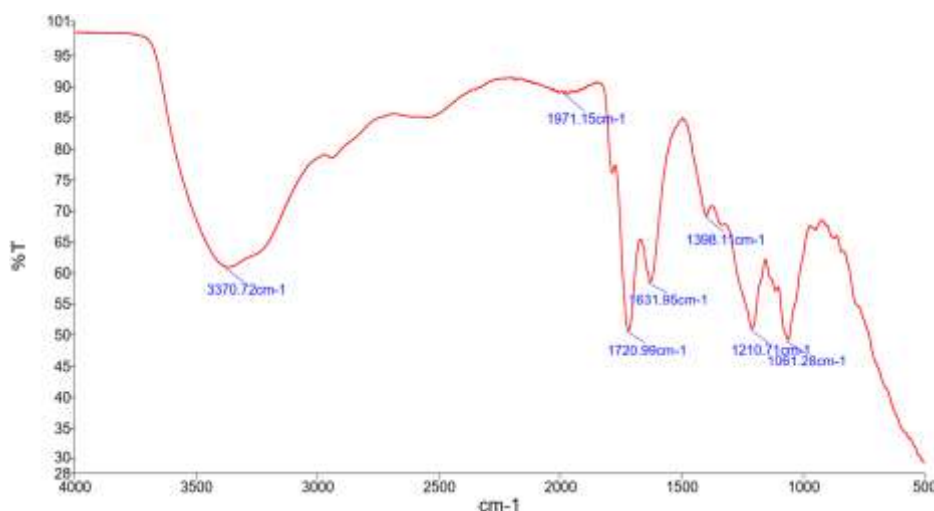


Figure 7. ATR–FTIR spectrum of untreated *Garcinia cambogia* rind oil

3.4 FTIR Confirmation of Chemical Modification

FTIR was used to confirm chemical modification and the FTIR spectrum obtained after epoxidation is as shown in Figure. 8. A number of changes were observed in the spectrum when compared with that of the untreated oil. The carbonyl absorption was still present with the main band at 1711.13 cm^{-1} in the chemically modified sample and 1720.99 cm^{-1} in the untreated sample. This absorption was still present after the modification, suggesting that the

carbonyl-containing structure was still present. The absorption due to the unsaturation around 1631.95 cm^{-1} was decreased following chemical modification. This is in line with the carbon–carbon double bond consumption in the epoxidation reaction. The most significant findings were two new absorption bands at 908.91 cm^{-1} and 835.08 cm^{-1} . These bands are typical of vibrations that are related to oxirane/epoxy functionality. Formation of oxirane and the reduction of unsaturation in vegetable-oil epoxidation has been monitored by FTIR technique. Spectroscopic

evidence for the chemical modification of the unsaturated sites on the *Garcinia cambogia* oil is obtained by observing the simultaneous decrease in the absorption band associated with the unsaturated sites and the appearance of the new absorption band associated with the oxirane group. The observed behaviour is similar to that of other vegetable oils, which have been previously reported to follow the epoxidation behaviour. Conversion of unsaturated structures to oxirane functionalities has been reported in the case of canola, soybean and mahua oil. Interpretation of the FTIR results should be done properly, however. Both spectra confirm a structural change, but they do not in themselves provide any information with regards to the degree of modification, the mechanical qualities or the applicability of the modified oil for a specific application in engineering. In the absence of quantitative oxirane oxygen content (OOC) titration or NMR spectroscopy, the present FTIR data

provide qualitative spectroscopic confirmation of oxirane ring formation rather than a quantitative measure of fractional chemical conversion.

In addition to the functional group conversion, the spectrum of the epoxidized oil reflects the overall structural retention of the long-chain hydrocarbon architecture as summarized comparison table depicted in Table. 3. The emergence of prominent aliphatic C–H stretching vibrations 2921.86 cm^{-1} and 2852.03 cm^{-1} alongside the CH_2 rocking mode 732.15 cm^{-1} confirms that the aliphatic hydrocarbon chains remained intact post-modification. Furthermore, minor shifts observed in C–H bending (1454.02 cm^{-1} & 1375.58 cm^{-1}) and the C–O stretching region (1230.73 – 1045.64 cm^{-1}) demonstrate the overall retention of oxygen-containing functionalities and backbone stability following chemical treatment.

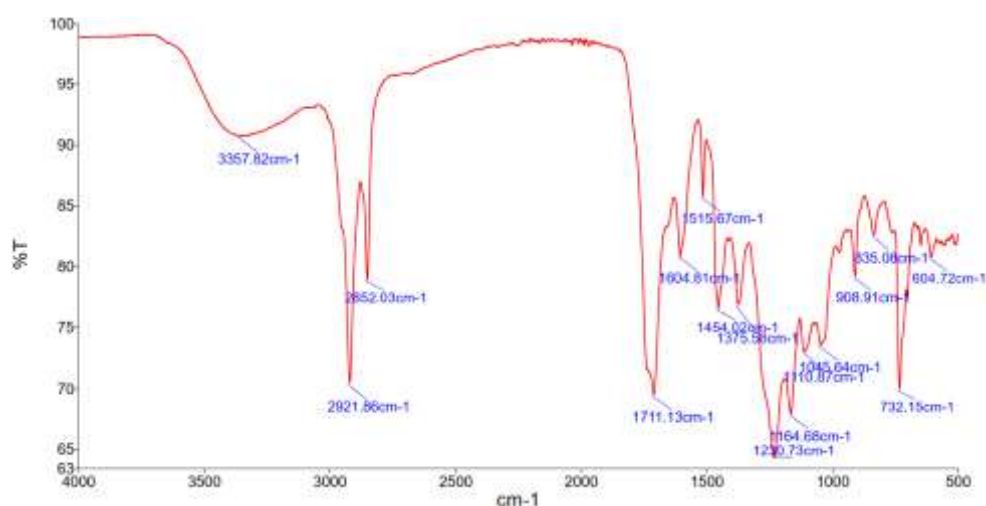


Figure 8. ATR-FTIR spectrum of epoxidized *Garcinia cambogia* rind oil

Table 3. Summarized Comparison Table based on the presence of various functional group

Functional group	Original oil (cm^{-1})	Epoxidized oil (cm^{-1})	Band Assignment / Structural Significance
O–H stretch	3370.72	3357.82	Hydroxyl groups in polar organic acids / trace moisture
Aliphatic C–H stretching	—	2921.86, 2852.03	Asymmetric and symmetric C–H stretching of hydrocarbon backbone
Carbonyl (C=O) stretching	1720.99	1711.13	Ester / carboxylic acid carbonyl backbone retention
C=C (unsaturation)	1631.95	Reduced (1604.81 region)	Consumption of olefinic double bonds via peracid reaction
CH bending	1398.11	1454.02, 1375.58	–CH ₂ – and –CH ₃ – deformation modes
C–O stretching	1210.71, 1061.28	1230.73, 1164.68, 1110.87, 1045.64	Ester / ether C–O single bond stretching
Epoxy (oxirane) ring vibration	Absent	908.91, 835.08	Symmetric and asymmetric oxirane (C–O–C) ring stretching
CH ₂ rocking	—	732.15	Long-chain aliphatic methylene rocking

3.5 Structural Significance of Epoxidation

The structure of the molecule is significant in the epoxidation reaction. The main feature of the present modification is that the molecular structure of the material formed is renewable and is modified by the introduction of epoxy functionality. (Varghese &

Gopalakrishnan, 2026) Oil before modification has carbon–carbon unsaturated sites that can be a site of chemical reaction. Comparison of various functional groups before and after epoxidation is shown in Table. 3. These sites after epoxidation show evidence in the spectrum of the formation of oxirane-containing structures. (Qian et al., 2023) As a result, the chemical

modification modifies the functionality of the oil, but does not simply change its physical properties. It is significant for an engineering application. The chemically active functional groups are called epoxy groups which can undergo further polymerizations and cross-linking reactions. (Noè et al., 2021) Epoxidized vegetable oils have thus been explored as ingredients for bio-based epoxy resins, thermosets and other polymeric products. In the past, for instance, the thermomechanical behaviour of systems based on epoxy and epoxidized vegetable oils has been the subject of study, as well as the development of fully or partially bio-based thermoset systems based on EVO. (Parada Hernandez et al., 2017) The use of the epoxidized *Garcinia cambogia* oil in the present work does not imply that the mechanical or thermomechanical properties of this oil will be the same as those found in other vegetable oil-based systems. Instead, it is the literature that makes it clear that the incorporation of epoxide groups into vegetable oil-based materials can lead to development of new materials. This gives the engineering significance of the present chemical study which is based not on the fact that the chemicals have an engineering application but on the fact that the results of the GC-MS and FTIR tests lay a structural groundwork for further investigation.

3.6 Future Experimental Pathway

The chemically modified *Garcinia cambogia* oil could be a promising renewable molecular precursor for further studies in the field of engineering materials due to the introduction of the reactive oxirane functionality in the epoxidation process. (Kim, An, Park, & Song, 2007) Epoxidized vegetable-oil structures are also used in composite systems, where their chemical function could be used to contribute to interaction with other material system components. (Jin & Park, 2008) Likewise, surface engineering systems using vegetable oils are being studied for use as coatings. The applications are relevant from the machine design and mechanical engineering point of view as the final performance of the material is determined by the molecular structure, crosslinking behavior, interfacial interactions, mechanical and thermomechanical properties and characteristics. (Samper, Petrucci, Sanchez-Nacher, Balart, & Kenny, 2015) The present results show that the extracted oil has chemically diverse constituents which are unsaturated structures. These structures get chemically modified in the chosen epoxidation conditions and the resulting modified oil provides spectroscopic evidence of the presence of epoxy functionality. These observations provide the chemical basis for subsequent engineering investigations. Because the primary objective was qualitative feasibility demonstration, the present study evaluated a single reaction trial, which inherently limits reporting statistical variability or kinetic confidence intervals. Consequently, future research pathways should incorporate systematic, independent multi-batch reaction replicates, response surface methodology (RSM) optimization, and statistical variance reporting (mean $\pm$

standard deviation) across varying molar ratios, temperatures, and reaction times (Varghese & Gopalakrishnan, 2026).

Further research could focus on epoxy resin formulation, thermoset preparation, coating formulation or incorporating into composite materials depending on the desired application. Empirical physical and tribological evaluations including kinematic viscosity, flash and fire point testing, oxidation stability, and friction coefficients represent necessary future testing to assess potential suitability as a bio-lubricant base stock or resin precursor (Wagner et al., 2001; Salimon et al., 2010; McNutt & He, 2016) What tests would be used would be dependent upon the material system created by the modified oil (Mustapha et al., 2014) Chemical functionality is important for material development, but is not the sole criteria for the performance of the material, and the engineering performance is a subject for future work.

4. CONCLUSION

In the present study, the *Garcinia cambogia* rind oil has been explored from the chemical characterization and structural functionalization point of view as a potential bio-based precursor. The oil extracted from the pericarp via traditional thermal aqueous extraction was found to be chemically heterogeneous as verified using GC-MS analysis at the Biofuel Regional Quality Testing Laboratory (BRQAL, GKVK, Bengaluru), resolving 21 identified constituents dominated by short-chain organic acids (propanoic acid, 27.24% relative area) and furanic derivatives (32.63% area) alongside fatty-acid-derived species (3.18% area). The unsaturated structures identified (such as 6-octadecenoic acid at 2.10% area and 13-docosenamide at 1.71% area) were used as the basis to investigate in-situ peracetic acid epoxidation as a strategy to add oxirane functionality. The oil was then chemically treated with an in-situ peracetic acid epoxidation system under fixed volumetric reactant conditions 10:3:10 (oil:glacial acetic acid:30% H_2O_2). Comparative ATR-FTIR analysis showed that there are clear differences in structure between the samples which were not treated and the modified samples. The untreated oil had absorptions typical of hydroxyl (3370.72 cm^{-1}), carbonyl (1720.99 cm^{-1}) and unsaturated (1631.95 cm^{-1}) functionalities, and the modified oil had decreased the absorption of the unsaturations (shifting to a reduced intensity band at 1604.81 cm^{-1}). Most importantly, new absorption bands were observed at 908.91 and 835.08 cm^{-1} , which provide qualitative spectroscopic evidence for the presence of oxirane (C-O-C) ring oxirane/epoxy functionality after chemical modification. Additionally, the presence of the carbonyl absorption 1711.13 cm^{-1} shows that the main carbonyl structure was still present after the reaction. Rather than claiming demonstrated application performance or mechanical utility, this study establishes that *Garcinia cambogia* rind oil can be chemically functionalized into an oxirane-bearing molecular precursor. The study shows how the structures

of such chemically diverse pericarp-derived molecules, can have reactive sites that can be functionalized via epoxidation, resulting in an isolated product with new epoxy functionality. The epoxy structures generated from the epoxidized vegetable-oil frameworks have been shown in previous studies to be precursors for bio-based epoxy systems, thermosets, biolubricant basestocks coatings and composites (Wagner et al., 2001; Malburet et al., 2020). Based on the current findings, therefore, pericarp lipophilic extracts structures derived from *Garcinia cambogia* can serve as a qualitative chemical

basis to investigate various renewable precursor systems. The next step should then be to conduct multi-batch process optimization and draw up appropriate formulations from the epoxidized material for systematic empirical evaluation of physical, tribological, mechanical, thermal and thermomechanical properties (Varghese & Gopalakrishnan, 2026). The prospective future investigations would be conducted to assess if the chemically modified *garcinia cambogia* oil can play an effective role in a certain engineering-material system.

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Ravikiran

Assistant Professor,
Department of Mechanical Engineering,
The National Institute of Engineering,
Mysuru, Karnataka,
India
ORCID 0000-0002-4027-2532

Shreyas G Kashyap

PG - Student,
Department of Mechanical Engineering,
The National Institute of Engineering,
Mysuru, Karnataka,
India
ORCID 0009-0003-5812-6702

Ravikumar Beeranur

Associate Professor,
Department of Mechanical Engineering,
The National Institute of Engineering,
Mysuru, Karnataka,
India
ORCID 0000-0002-1826-5635

Rupesh S

Assistant Professor,
Department of Mechanical Engineering,
PES College of Engineering,
Mandya, Karnataka,
India
ORCID 0000-0002-6460-8299

Ganesh Arjun S

UG - Student,
Department of Mechanical Engineering,
The National Institute of Engineering,
Mysuru, Karnataka,
India
ORCID 0009-0005-7851-5308

Yathik Aiyappa S C

UG - Student,
Department of Mechanical Engineering,
The National Institute of Engineering,
Mysuru, Karnataka,
India
ORCID 0009-0007-2826-0268
