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RESEARCH ARTICLE

A new insight for the catalytic synthesis of phytol from *Gmelina arborea* leaves

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Abstract - The conversion of waste biomass into valuable products like biofuels and biochemicals is a rapidly growing research area. Among these biochemicals, phytol serves as an essential precursor for the fuel, pharmaceutical, and food sectors. The foliage of the deciduous tree *Gmelina arborea* offers an abundant yet underexploited biomass source. This work aims to explore the catalytic production of phytol from *Gmelina arborea* leaves, using barium chloride ($BaCl_2$) as a catalyst. The catalyst concentrations were varied at 0.5% and 1.0% across reaction temperatures ranging from 60 to 90 °C. Phytol output showed a positive curvilinear (quadratic) response to temperature, reaching its maximum at 80 °C. The highest phytol yields of 24.17% (1,985.06 mg/g) and 15.30% (1,304.6 mg/g) were obtained at catalyst loadings of 0.5% and 1.0%, respectively. These results emphasise the promise of *Gmelina arborea* leaves as a sustainable and valuable feedstock for phytol production, aligning with global efforts to utilise waste materials into beneficial resources.

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1. Introduction

The world has shown growing concern about environmental issues, such as climate change and pollution caused by petroleum and its derivatives. Progressive work by researchers worldwide is evident in the development of solutions to replace petroleum-based resources with biomass [1,2]. Biomass, for instance, is a sustainable and environmentally beneficial solution, as it is renewable, carbon neutral, widely available, and poses fewer health risks than petroleum-based materials [3]. Phytol (3,7,11,15-tetramethyl-2-hexadecen-1-ol, $C_{20}H_{40}O$, CAS number is 150-86-7), for instance, is a diterpene alcohol that can be naturally produced and derived from biomass. This compound has a molecular weight of 296.53 g/mol, a density of 0.85 g/ml and a boiling point of 202–204 °C [4-6]. It is also widely known for its antimicrobial, anti-inflammatory, and anticancer properties, as well as antiparasitic, anti-anxiety, and antioxidant effects [7,8]. Phytol belongs to the class of acyclic hydrogenated diterpene alcohols [9,10]. Phytol is used in various industries, including as a flavouring agent in the food industry, as a component in pharmaceuticals such as vitamins E and K, and as an ingredient in fragrances for perfumery, agriculture, and cosmetics [11-13]. Besides that, it is a strategic starting molecule that can be developed as a precursor for fuels, lubricants, surfactants, and speciality chemicals [14,15]. Tracy et al. [16] reported that phytol has also gained recognition as a promising feedstock for gasoline production since it can be cracked to yield hydrocarbons in the gasoline range (C_6 to C_{12}) [16]. Phytol can also be used as an additive for diesel fuels due to its physical and chemical properties that are comparable to those of diesel fuels [3,17]

Phytol production from biomass that contains chlorophyll typically involves hydrolysis, decarboxylation, and rearrangement of specific phytochemical precursors. The yield of phytol and other chemical derivatives, such as chlorophyllide or pheophytin, is highly dependent on the reaction conditions and catalyst type. There are conventional production methods that involve extracting phytol from bacteria, algae, and plants [6,18]. In 1909, German chemist Richard Willstätter first isolated phytol by hydrolysing chlorophyll [19]. Interestingly, phytol has also been detected in nut skins and in dairy, beef, and fish products [20]. Several studies have reported phytol synthesis from diverse sources such as *Lathyrus ochrus*, *Forsythia koreana*, *Gaillardia pulchalla*, *Solanum spirale*, *Senna hisale*, and *Sene ocidevtalis* and green alga (*Chaetomorpha antinnina)* [21,22]. Phytol production has also been documented from silkworm faeces in China and Japan [24-26]. Venkatesh Kumar et al. [23] reported phytol yield of 5.8% from hydrodistillation of *Cnestis ferruginea*. *Gmelina arborea*, on the other hand, is a fast-growing tree that produces abundant renewable leaves for biomass. The plant is suitable as a feedstock for phytol synthesis because its leaves contain high levels of chlorophyll, terpenoids, and other important phytochemicals [24]. This plant is easy to grow under diverse climatic conditions and requires minimal care from farmers [25]. The non-edible leaves are frequently discarded, offering an environmentally friendly and economically viable resource for the production of bio-based chemicals [26].

Despite the growing recognition of phytol as a versatile platform chemical for fuel, pharmaceutical, and food applications, its sustainable production remains constrained by several critical limitations. Existing phytol synthesis routes predominantly rely on hydrodistillation or solvent extraction from edible or high-value plant species, as well as from algae and silkworm faeces. These feedstocks often compete with food and medicinal applications, driving up costs and undermining the long-term viability of phytol-based biorefineries. Furthermore, conventional extraction methods, such as hydrodistillation and ethanolic/methanolic extraction, are energy-intensive, may degrade thermally sensitive compounds, and lack the selectivity needed for efficient phytol recovery [27]. To date, no study has systematically investigated the catalytic synthesis of phytol from *Gmelina arborea* leaves using barium chloride ($BaCl_2$) as a mild, cost-effective catalyst for the hydrolysis of chlorophyll into phytol from this feedstock. The influence of key process parameters, specifically, catalyst loading (e.g., 0.5% vs. 1.0%) and reaction temperature (60-90 °C), on phytol yield from

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Gmelina arborea remains uncharacterized. Moreover, the optimal reaction conditions that maximise phytol yield while minimising side reactions and over-coordination have not been established for this biomass source. Therefore, valorising waste leaf biomass of *Gmelina arborea* is essential for advancing circular bioeconomy goals and providing a scalable, economically viable alternative to petroleum-derived feedstocks. The present study seeks to fill this gap by evaluating the catalytic performance of $BaCl_2$ at varying temperatures (from 60 to 90 °C) and catalyst loadings (0.5% and 1.0% $BaCl_2$). The resulting products were characterised by gas chromatography-mass spectrometry (GC-MS) to confirm the identity of phytol and quantify yield. This work addressed the research gap in developing a simple, low-temperature, catalytic route for phytol production that avoids edible or high-value plants.

2. Materials and Method

2.1 Chemicals, Materials and Pretreatment

The *Gmelina arborea* leaves used in this study were obtained from the Kaduna Polytechnic, Kaduna, Nigeria. The leaves were cleaned by removing dirt through sorting, followed by thorough air-drying. The dried leaves were ground with a ceramic mortar and pestle, then sieved through 250- and 300-µm mesh sizes [28]. The glassware and equipment include sieves with 250- and 300-µm mesh sizes, distilled water, a ceramic mortar and pestle, a spatula, aluminium foil, filter cloth, a top-loading balance, a Gallenkamp hot plate fitted with a magnetic stirrer, a thermometer, and filter paper. Magnesium sulphate and barium chloride ($BaCl_2$) were of analytical grade.

2.2 Synthesis Process

A catalyst solution was prepared by dissolving 0.5% BaCl2 (0.25 g) in 500 mL of distilled water in a 1000 mL conical flask. The flask was then placed on a Gallenkamp hot plate equipped with a magnetic stirrer. Approximately 50 g of the pulverised leaves were added to the solution, and the mixture was covered. It was heated to 60 °C under continuous magnetic stirring. The reaction mixture was kept at 60 °C for 30 min, following the protocol established by Ali and Ibrahim [29]. After heating, the mixture was filtered twice: first through a filter cloth, then through filter paper. The resulting filtrate was collected in a 1000 mL beaker. The filtrate was dehydrated using magnesium sulphate, followed by phase separation in a separating funnel [30,31]. The dehydrated product was then weighed to determine its mass. The synthesis was repeated at different reaction temperatures (60, 70, 80, and 90 °C) while keeping the catalyst concentration fixed at 0.25 g (0.5% w/w of feed). A mild temperature range of 60-90 °C was selected to maintain gentle reaction conditions. In addition, four further experimental runs were carried out at the same temperature points (60, 70, 80, and 90 °C) using a higher catalyst loading of 1.0% (0.5 g $BaCl_2$ in 500 mL distilled water). The filtrates from each run were collected in 10 mL vials and subsequently analysed by GC-MS to determine their chemical composition [32].

2.3 Gas Chromatography-Mass Spectrometry

The procedure outlined by Ibrahim et al. [32] was followed with slight modification. The sample was derivatised by mixing 200 µL of the standard solution with 100 µL of trimethylsulfonium hydroxide (TMSH) and 20 µL of triethylamine (TEA) in sealed vials. The vials were then heated at 70 °C for 1 hour before GC-MS analysis. The GC-MS system used was a Varian 3800/4000. The DB-5 capillary column with dimensions of 30 mm × 0.25 mm and a 0.25 µm film thickness was used for chromatographic separation and identification. Nitrogen gas was used as carrier gas at a constant column head pressure of 10 psi. The oven temperature program began at 100 °C, held for 3 min, then increased at 8 °C/min to 300 °C. The temperature at the transfer line was set at 290 °C. Mass spectrometric detection was performed using a VG 7070E magnetic sector instrument operating in electron-impact ionisation mode. Mass spectra were recorded over a range of m/z 40–800 at a scan rate of 20 scans per second. A solvent delay of 330 s was incorporated to prevent detector saturation. Continuous signal monitoring ensured accurate and repeatable detection. The specific yield (in mg/g) is calculated using Eq. (1).

$$\text{Yield of phytol } (g) = \text{Yield of phytol}^{*}(\%) \times \textit{M}\text{ass of dehydrated product} \quad (1)$$

3. Results and Discussion

Table 1 shows the weight of the dehydrated products, yields of phytol (%) and its calculated yield in g obtained from the GC-MS. As seen, the dehydrated product ranges from 344.10 to 446.80 g for the 0.5% catalyst loading process, and from 408.10 to 428.12 g for the 1.0% catalyst loading process. The GC-MS chromatograms of dehydrated products are shown in Figure 1. The other important products obtained alongside phytol were nonadecane, O-decylhydroxylamine, 3-eicosene, and isopentanol. Although the phytol percentage yields obtained in this study were relatively moderate (6.16–24.17% at 0.5% catalyst loading and 7.23–15.30% at 1.0% catalyst loading), they remain significant when compared with reported values from other biomass sources [33]. For example, Rani et al. [34] reported a 10.3% phytol yield using ethanolic extraction from *Hydrilla verticillata*, while Anoor et al. [35] achieved an 11.4% yield through methanolic extraction of *Andrographis paniculata*.

Table 1. The products (g) of thermal hydrolysis of *Gmelina arborea* leaves and phytol yields

Descriptions	Unit	Reaction temperature (℃)			
		60	70	80	90
Catalyst loading (0.5%)					
Weight of dehydrated filtrate	g	422.70	344.10	412.40	446.80
Yield of phytol	%	6.16	7.40	24.17	11.78
Yield of phytol	g	26.04	25.48	99.25	52.62
Catalyst loading (1.0%)					
Weight of dehydrated filtrate	g	428.12	421.50	426.20	408.10
Yield of phytol	%	7.23	7.91	15.30	8.31
Yield of phytol	g	30.97	33.38	65.21	33.97

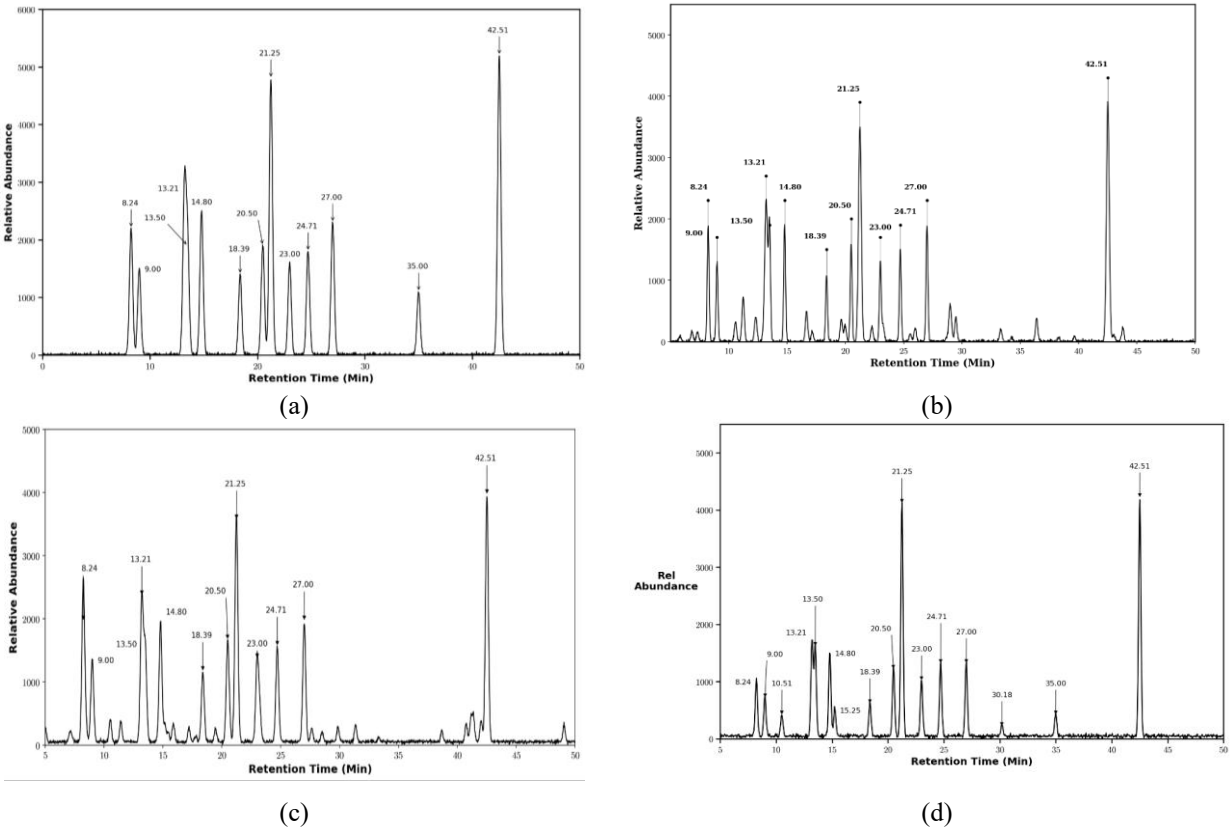

Figure 1. GC-MS chromatogram of the dehydrated product (a) 0.25 g catalyst and at 60℃, (b) 0.25 g catalyst and at 70℃, (c) 0.50 g catalyst and at 60℃ and (d) 0.50 g catalyst and at 70℃

Although hydrodistillation yields higher phytol levels, the economic value of these plant species often limits their feasibility for large-scale production. The higher cost of such species makes them less viable for sustainable phytol production than more accessible alternatives, such as *Gmelina arborea* leaves. Furthermore, phytol holds significant potential as a renewable energy source. Tracy et al. [16] reported that cracking phytol could yield up to 49.65% gasoline. Using *Gmelina arborea* leaves to produce phytol offers a sustainable alternative to petroleum-based fuels, thereby reducing reliance on non-renewable energy sources. The relationship between reaction temperature and phytol yield (mg/g of *Gmelina arborea* leaves) is depicted in Figure 2. The yield exhibited a quadratic trend as the reaction temperature increased from 60 °C to 90 °C, with a maximum at 80 °C. As shown, the yield achieved with a 0.5% $BaCl_2$ catalyst loading exceeded that obtained with a 1.0% catalyst loading. These results indicate that, under experimental conditions, the optimal parameters for maximising phytol yield from *Gmelina arborea* leaves are a reaction temperature of 80 °C and a catalyst loading of 0.5% $BaCl_2$. The potential of this process is further underscored by the substantial global demand for phytol. According to Saduka et al. [36], the estimated annual conversion of chlorophyll for phytol production was approximately 11×10^8 tons in 2002. In contrast to conventional methods, which typically involve chlorophyll extraction followed by saponification [37], the catalytic synthesis offers a more efficient, streamlined approach to phytol production.

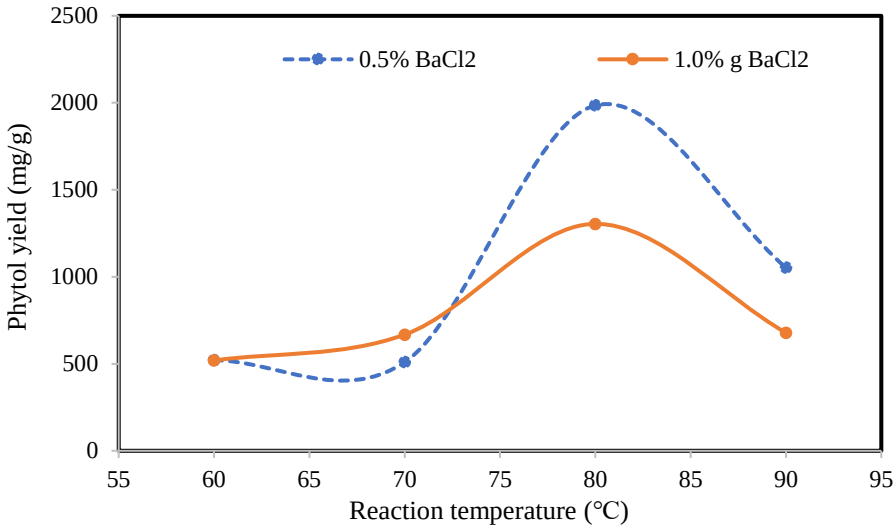

Figure 2. Phytol yield vs reaction temperature

Benelli et al. [57] reported a phytol content of 9.2% in *Stevia rebaudiana* (Asteraceae). Drinić et al. [38] found that the diterpene composition of extracts from *Sideritis raeseri* obtained by microwave-assisted hydrodistillation and conventional hydrodistillation were 13.26% and 8.59%, respectively. In another related study, Lemouchi et al. [39] reported a phytol content of 11.5% in the essential oil of *Psoralea bituminosa* extracted via hydrodistillation. Jiangseubchatveera et al. [40] reported that the essential oil from the leaves of *Graptophyllum pictum* (L.) Griff., isolated by hydrodistillation, contained 75.7% phytol. Additionally, Slama et al. [41] found that the essential oil extracted from the aerial parts of *Borago officinalis* L. using hydrodistillation contained 27.92% phytol. In the present study, a maximum phytol yield of 24.17% (equivalent to a specific yield of 1,985.06 mg/g) was achieved from the 0.5% barium chloride-catalysed thermal hydrolysis of *Gmelina arborea* leaf biomass at 80 ℃ over a reaction time of 30 min.

Table 2. Comparative yields of phytol from different plant species obtained from the literature

Plant Species	Extraction Method	Phytol Content (%)	References
Gmelina arborea leaves	Barium chloride catalysed thermal hydrolysis (0.5% $BaCl_2$, 80 °C, 30 min)	24.17%	Present study
Stevia rebaudiana (Asteraceae)	Not specified (likely hydrodistillation)	9.20%	[27]
Sideritis raeseri	Microwave-assisted hydrodistillation	13.26%	[38]
Sideritis raeseri	Conventional hydrodistillation	8.59%	[38]
Psoralea bituminosa	Hydrodistillation	11.50%	[39]
Graptophyllum pictum (L.) Griff. (leaves)	Hydrodistillation	75.70%	[40]
Borago officinalis L. (aerial parts)	Hydrodistillation	27.92%	[41]

Table 2 results reveal considerable variation in phytol content across plant species and extraction methods, ranging from 8.59% (*Sideritis raeseri*, conventional hydrodistillation) to 75.7% (*Graptophyllum pictum*, hydrodistillation). This wide range reflects inherent differences in plant biochemistry, tissue type, and extraction efficiency. Notably, conventional hydrodistillation, the most reported method, yielded moderate to high phytol percentages in several species: 11.5% in *Psoralea bituminosa*, 27.92% in *Borago officinalis*, and the exceptionally high 75.7% in *Graptophyllum pictum*. However, the same method yielded only 8.59% for *Sideritis raeseri*, whereas microwave-assisted hydrodistillation improved it to 13.26%, highlighting the influence of extraction technology. In comparison, the present study achieved a phytol yield of 24.17% using a fundamentally different approach: barium chloride-catalysed thermal hydrolysis under mild atmospheric conditions (80 °C, 30 min). This value exceeds those obtained by conventional hydrodistillation for *Stevia rebaudiana* (9.2%), *Sideritis raeseri* (8.59%), and *Psoralea bituminosa* (11.5%), and is comparable to that of *Borago officinalis* (27.92%). Although it is lower than 75.7% reported for *Graptophyllum pictum*, the latter may represent an outlier or a species exceptionally rich in phytol. Crucially, the catalytic method employs non-edible, waste biomass (*Gmelina arborea* leaves) rather than food or high-value plants, offering a distinct sustainability advantage. Moreover, the short reaction time (30 min) and mild temperature (80 °C) contrast favourably with energy-intensive hydrodistillation. Thus, while the absolute yield is moderate, the combination of feedstock sustainability, process simplicity, and competitive yield positions this catalytic route as a promising alternative for scalable, green phytol production.

4. Conclusions

This study successfully demonstrates a novel, mild, and catalytic route for the synthesis of phytol from the abundant, non-edible biomass of *Gmelina arborea* leaves, using barium chloride ($BaCl_2$) as a cost-effective catalyst. The findings unequivocally establish that both reaction temperature and catalyst loading are critical determinants of phytol yield, exhibiting a non-linear, quadratic relationship. The optimal conditions, a moderate catalyst loading of 0.5% $BaCl_2$ at a reaction temperature of 80 °C for 30 min, yielded a maximum phytol output of 24.17% (equivalent to 1,985.06 mg/g). This performance is highly competitive with conventional hydrodistillation across various plant species and, more importantly, is achieved using a simpler, less energy-intensive process and a sustainable, waste-based feedstock. A key insight is the counterintuitive observation that a lower catalyst concentration (0.5%) consistently outperformed the higher loading (1.0%) across all temperatures. This suggests that beyond an optimal threshold, excess $BaCl_2$ may promote undesirable side reactions, over-coordination, or partial degradation of phytol, highlighting the necessity for precise process control rather than simply maximising catalyst input. The GC-MS analysis not only confirmed phytol as the primary product but also identified valuable co-products (e.g., nonadecane, 3-eicosene), underscoring the potential of *Gmelina arborea* leaves as a feedstock for an integrated biorefinery. The coexistence of these compounds highlights the chemical richness of *Gmelina arborea* leaves and their suitability for integrated biorefinery applications. Overall, the $BaCl_2$-catalysed process provides a simple, low-cost, and environmentally benign route for phytol production, aligning with sustainable chemistry and circular bioeconomy objectives while reducing dependence on edible or high-value plant resources.

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Declaration of Competing Interest

The author declares no conflicts of interest.

CRediT Authorship Contribution Statement

H. Ibrahim: Resources; Conceptualization; Formal analysis; Writing - original draft
A.M. Ali: Visualization; Supervision
F.H. Mukhtar: Methodology; Data curation

Availability of Data and Materials

Data sharing does not apply to this article as no new datasets were generated or analysed in this study.

Ethics Statement

This study did not involve human participants or animal subjects. Ethical approval was therefore not required for this research.

Generative Artificial Intelligence Declarations

The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

References

[1] Muh E, Tabet F, Amara S. Biomass conversion to fuels and value-added chemicals: a comprehensive review of the thermochemical processes. Clean Energy. 2021;4(1):3-25. https://doi.org/10.2174/2405463103666191022121648
[2] Mori R. Replacing all petroleum-based chemical products with natural biomass-based chemical products: A tutorial review. RSC Sustainability. 2023;1(2):179-212. https://doi.org/10.1039/D2SU00014H
[3] Wang J, Xu L, Xing L, Shi Y. The fragmentation behavior and variation of the pristane-phytane ratios of pure phytol in conditions of clay catalysis. Petroleum Science and Technology. 2017;35(23):2216-2220. https://doi.org/10.1080/10916466.2017.1399140
[4] Islam MT, Ayatollahi SA, Zihad SN, Sifat N, Khan MR, Paul A, Salehi B, Islam T, Mubarak MS, Martins N, Sharifi-Rad J. Phytol anti-inflammatory activity: Pre-clinical assessment and possible mechanism of action elucidation. Heliyon. 2020;6(4):e03264. https://doi.org/10.14715/cmb/2020.66.4.31
[5] Kanjikar AP, Londonkar RL. Isolation, purification and characterization of terpene from Ficus krishnae. Pharmacophore. 2020;11(2):30-35. https://pharmacophorejournal.com/4MZL76L
[6] Saranya C. Pharmacokinetic evaluation of phytol in rats [Doctoral dissertation]. Kerala Veterinary and Animal Sciences University; 2022.

[7] Al-Khayri JM, Banadka A, Nandhini M, Nagella P, Al-Mssallem MQ, Alessa FM. Essential oil from *Coriandrum sativum*: A review on its phytochemistry and biological activity. Molecules. 2023;28(2):696. https://doi.org/10.3390/molecules28020696
[8] Abd Elkader H-TAE, Essawy AE, Al-Shami AS. Astragalus species: Phytochemistry, biological actions and molecular mechanisms underlying their potential neuroprotective effects on neurological diseases. Phytomedicine. 2022;202:113293. https://doi.org/10.1016/j.phytochem.2022.113293
[9] Luhata LP, Hirao M, Mori N, Usuki T. Chemical composition and antioxidant activity of the hexane fraction from leaf extracts of *Odontonema strictum*. American Journal Essential Oils Natural Products. 2023;11(1):12-16.
[10] Arsana IN, Juliasih NKA, Widyantari ASS. GC–MS analysis of bioactive compounds in lime leaf ethanol extract (*Citrus amblycarpa* (Hassk.) Ochse), and its potential as a traditional medicine agents. Journal of Pharmaceutical Negative Results. 2024;10(4):1994-2006. https://doi.org/10.29303/jppipa.v10i4.3735
[11] Abbas F, Zhou Y, O'Neill Rothenberg D, Alam I, Ke Y, Wang H-C. Aroma components in horticultural crops: chemical diversity and usage of metabolic engineering for industrial applications. Plants. 2023; 12(9): 1748. https://doi.org/10.3390/plants12091748
[12] Kliszcz A, Danel A, Puła J, Barabasz-Krasny B, Możdżeń K. Fleeting beauty—The world of plant fragrances and their application. Molecules. 2021;26(9):2473. https://doi.org/10.3390/molecules26092473
[13] Mendiola JA, Santoyo S, Cifuentes A, Reglero G, Ibanez E, Señoráns FJ. Antimicrobial activity of sub-and supercritical CO_2 extracts of the green alga *Dunaliella salina*. Journal of Food Protection. 2008;71(10):2138-43. https://doi.org/10.4315/0362-028X-71.10.2138
[14] Prabha SP, Karthik C, Chandrika SH. Phytol–A biosurfactant from the aquatic weed *Hydrilla verticillata*. Biocatalysis and Agricultural Biotechnology. 2019;17:736-742. https://doi.org/10.1016/j.bcab.2019.01.026
[15] Laurens LM, Markham J, Templeton DW, Christensen ED, Van Wychen S, Vadelius EW, et al. Development of algae biorefinery concepts for biofuels and bioproducts; a perspective on process-compatible products and their impact on cost-reduction. Energy & Environmental Science. 2017;10(8):1716-1738. https://doi.org/10.1039/C7EE01306J
[16] Tracy NI, Crunkleton DW, Price GL. Gasoline production from phytol. Fuel. 2010;89(11):3493-3497. https://doi.org/10.1016/j.fuel.2010.06.022
[17] Ramírez A, Aggarwal S, Som S, Rutter T, Longman DJ. Effects of blending a heavy alcohol ($C_{20}H_{40}O$) with diesel in a heavy-duty compression-ignition engine. Fuel. 2014;136:89-102. https://doi.org/10.1016/j.fuel.2014.06.039
[18] Ramírez AI, Som S, LaRocco LA, Rutter TP, Longman DE. Investigating the use of heavy alcohols as a fuel blending agent for compression ignition engine applications. In: Proceedings of the ASME Internal Combustion Engine Division Spring Technical Conference; 2012 May 6-9; Torino, Italy. New York: ASME; 2012. https://doi.org/10.1115/ICES2012-81169
[19] Alves E, Dias M, Lopes D, Almeida A, Domingues MR, Rey F. Antimicrobial lipids from plants and marine organisms: An overview of the current state-of-the-art and future prospects. Antibiotics. 2020;9(8):441. https://doi.org/10.3390/antibiotics9080441
[20] Leroy F. A century of Nobel Prize recipients: chemistry, physics, and medicine. Boca Raton: CRC Press; 2003.
[21] Bobe G, Zhang Z, Kopp R, Garzotto M, Shannon J, Takata Y. Phytol and its metabolites phytanic and pristanic acids for risk of cancer: current evidence and future directions. European Journal of Cancer Prevention. 2020;29(2):191-200. https://doi.org/10.1097/CEJ.0000000000000534
[22] Fahim M, Shrivastava B, Shrivastava A, Ibrahim M, Parveen R, Ahmad S. Review on extraction methods, antioxidant and antimicrobial properties of volatile oils. Advanced Pharmaceutical Journal. 2017;6(2):5-46. https://doi.org/10.21276/ap.2017.6.2.2
[23] Venkatesh Kumar R, Srivastava D. Silkworm: A unique creature for natural products. In: Natural materials and products from insects: Chemistry and applications. Cham: Springer; 2020. p. 95-109. https://doi.org/10.1007/978-3-030-36610-0_6
[24] Ogunwande IA, Avoseh NO, Flamini G, Hassan AS, Ogunmoye AO, Ogunsanwo AO, et al. Essential oils from the leaves of six medicinal plants of Nigeria. Natural Product Communications. 2013;8(2):1934578X1300800229. https://doi.org/10.1177/1934578X1300800229
[25] Tamang M, Chettri R, Vineeta, Shukla G, Bhat JA, Kumar A, et al. Stand structure, biomass and carbon storage in *Gmelina arborea* plantation at agricultural landscape in foothills of Eastern Himalayas. Sustainability. 2021;10(4):387. https://doi.org/10.3390/land10040387
[26] Rangappa K, Singh NR, Janyanaik Joga R, Mohapatra KP, Chandra P, Choudhury BU, et al. Tree crop interactions, productivity and physiological efficiency of understorey crops in *Alnus nepalensis* and *Gmelina arborea* based agroforestry systems in Eastern Himalayas. Frontiers in Forest and Global Change. 2025;9:1494371. https://doi.org/10.3389/fsufs.2025.1494371
[27] Benelli G, Pavela R, Drenaggi E, Desneux N, Maggi F. Phytol, (E)-nerolidol and spathulenol from *Stevia rebaudiana* leaf essential oil as effective and eco-friendly botanical insecticides against *Metopolophium dirhodum*. Industrial Crops and Products. 2020;155:112844. https://doi.org/10.1016/j.indcrop.2020.112844
[28] Lal RK, Chanotiya CS, Kumar A. The prospects and potential of the horticultural and pharmacological medicinal herb senna (*Cassia angustifolia* Vahl.): A review. Trends in Horticulture. 2023;3(1):1-12. https://doi.org/10.48130/TIH-2023-0020

[29] Ali AM, Ibrahim H. Conversion of waste biomass into valuable platform furan-based-compounds. American Journal of Advanced Industrial Research. 2023;6(1):553-559.
[30] Ibrahim H, Ali AM. A new strategy to synthesize pentyl 2-hydroxy benzoate from renewable *Gmelina arborea* leaves. American Journal of Advanced Industrial Research. 2023;6(1):232-236.
[31] Ibrahim H, Ali AM. Advanced research in the synthesis of phthalic acid using waste *Gmelina arborea* leaves and barium chloride catalyst. Advanced Research Journal of Biological Innovation. 2023;4:1-6. htpps://doi.org/10.47721/ARJB20230401008
[32] Ibrahim H, Ali AM, Mukhtar FH. Investigating the application of barium chloride catalyst for synthesis of phthalic acid esters from Gmelina arborea leaves. International Journal of Engineering Processing and Safety Research. 2024;5(5):132-141. https://doi.org/10.28924/2291-8639-22-2024-132
[33] Ibrahim H, Jibia SA, Magaji S, Muhammad I. Biochemicals extraction for sustainable feedstocks from dried leaves of *Gmelina arborea*. Nigerian Journal of Technological Research. 2022;17(1):91-95. https://www.ajol.info/index.php/njtr/article/view/238748
[34] Rani J, Kapoor M, Dhull SB, Goksen G, Jurić S. Identification and assessment of therapeutic phytoconstituents of Catharanthus roseus through GC-MS analysis. Scientia Pharmaceutica. 2023; 10(6): 340. https://doi.org/10.3390/separations10060340
[35] Anoor PK, Yadav AN, Rajkumar K, Kande R, Tripura C, Naik KS, et al. Methanol extraction revealed anticancer compounds Quinic Acid, 2 (5H) Furanone and Phytol in *Andrographis paniculata*. Journal of Pharmaceutical Research International. 2022;17(5):151. https://doi.org/10.3892/mco.2022.2584
[36] Sadukha S, Mehta B, Chatterjee S, Ghosh A, Dineshkumar R. Sequential downstream process for concurrent extraction of lutein, phytol, and biochemicals from marine microalgal biomass as a sustainable biorefinery. ACS Sustainable Chemistry & Engineering. 2023;11(2):547-558. https://doi.org/10.1021/acssuschemeng.2c04804
[37] Yang Z, Li F, Shen S, Wang X, Nihmot Ibrahim A, Zheng H, et al. Natural chlorophyll: A review of analysis methods, health benefits, and stabilization strategies. Critical Reviews in Food Science and Nutrition. 2025;65(16):3069-3083. https://doi.org/10.1080/10408398.2024.2356259
[38] Drinić Z, Pljevljakušić D, Janković T, Zdunić G, Bigović D, Šavikin K. Hydro-distillation and microwave-assisted distillation of *Sideritis raeseri*: Comparison of the composition of the essential oil, hydrolat and residual water extract. Sustainable Chemistry and Pharmacy. 2021; 24100538. https://doi.org/10.1016/j.scp.2021.100538
[39] Lemouchi R, Selles C, Dib ME, Benmansour N, Allal A, Tabti B,et al. Chemical composition and antioxidant activity of essential oil and hydrosol extract obtained by hydrodistillation (HY) and liquid–liquid extraction (LLE) of Psoralea bituminosa. Journal of Herbs, Spices & Medicinal Plants. 2017;23(4):299-307. https://doi.org/10.1080/10496475.2017.1329765
[40] Jiangseubchatveera N, Liawruangrath B, Liawruangrath S, Teerawutgulrag A, Santiarworn D, Korth J, et al. The chemical constituents and the cytotoxicity, antioxidant and antibacterial activities of the essential oil of *Graptophyllum pictum* (L.) Griff. Journal of Essential Oil Bearing Plants. 2015;18(1): 1-17. https://doi.org/10.1080/0972060X.2014.935036
[41] Slama M, Slougui N, Ounnas D, Benaissa A, Belhattab I. Hydrodistillation optimization for *Borago officinalis* L. essential oil and its chemical composition analysis. Chemistry & Biodiversity. 2025; 24(2):e202402478. https://doi.org/10.1002/cbdv.202402478