

LC–MS/MS-Based Metabolite Profiling of *Eriolaena quinquelocularis* (Wight & Arn.) Drury Leaf Extract

Saurav Gaikwad

saurav.botany01@gmail.com

Savitribai Phule Pune University

Ramakant Patil

Savitribai Phule Pune University

Darshan Kokate

M.V.P's K.S.K.W College CIDCO Nashik Maharashtra India

Research Article

Keywords: *Eriolaena quinquelocularis*, LC–MS/MS, metabolite profiling, phytochemicals, phenolic acids, flavonoids, fatty acids, medicinal plants, untargeted metabolomics

Posted Date: October 21st, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-11160557/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License. [Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Eriolaena quinquelocularis (Wight & Arn.) Drury is a tree species of the family Malvaceae with a history of ethnomedicinal use, yet its chemical composition remains poorly documented. The present study aimed to characterize the metabolite profile of the leaves using untargeted liquid chromatography–tandem mass spectrometry (LC–MS/MS). Fresh leaves were collected, shade-dried, powdered, and extracted with LC–MS-grade methanol. The resulting extract was subjected to LC–ESI–MS/MS analysis using a triple quadrupole–QTRAP mass analyser in both positive and negative ionization modes. Chromatographic separation was performed on a reversed-phase C18 column using 0.1% formic acid and acetonitrile/methanol (50:50, v/v) as the mobile phases. Metabolite annotation was based on precursor ion masses, fragmentation patterns, and comparison with reference spectra in the NIST 2023 spectral library. A total of 46 metabolites were putatively identified, representing diverse chemical groups, including branched-chain, cyclopropane, saturated, monounsaturated, polyunsaturated and very-long-chain fatty acids, as well as organic acids, phenolic acids, and flavonoids. Several of the annotated metabolites have previously been associated with antioxidant, antimicrobial, antidiabetic, and anticancer properties in the literature. The present findings provide the first comprehensive LC–MS/MS-based characterization of the leaf metabolite profile of *E. quinquelocularis*. The chemical diversity detected in the extract highlights the species as a promising source of bioactive metabolites and provides a foundation for subsequent targeted isolation, structural confirmation, and experimental evaluation of their biological activities. The study also contributes baseline phytochemical information that may support future research on the medicinal, nutraceutical, and functional potential of this underexplored species.

1. Introduction

Medicinal plants have served as an indispensable source of therapeutic agents since antiquity and continue to contribute substantially to modern healthcare systems and drug discovery programmes. The World Health Organization estimates that a significant proportion of the global population relies on plant-derived medicines for primary healthcare needs. The therapeutic importance of medicinal plants is primarily attributed to their extraordinary diversity of bioactive metabolites, many of which have provided templates for the development of clinically important drugs.^{1,2,3,4} Consequently, systematic phytochemical investigations of medicinal plants have become an essential component of natural product research and pharmaceutical development.

Plants produce a remarkable array of metabolites that are broadly classified into primary and secondary metabolites. Primary metabolites, including carbohydrates, proteins, amino acids, nucleic acids, and lipids, are directly involved in growth and metabolic processes. Unlike primary metabolites, secondary metabolites such as phenolic compounds, flavonoids, alkaloids, terpenoids, tannins, coumarins, lignans, glycosides, and steroids play critical ecological roles. They also account for the many biological functions of medicinal plants. These compounds serve as adaptive responses of plants to environmental factors. They also account for the different forms of plant defenses against different stressors such as pathogens and herbivores as well as UV radiation and other forms of abiotic stresses.

The plant kingdom is estimated to possess an enormous repertoire of structurally diverse metabolites. These metabolites' qualitative and quantitative compositions vary by species, stage, location, environmental conditions, and genotype. For a more thorough understanding of plant physiology, adaptation, their interrelation based on secondary metabolites, and their potential uses in medicine, a detailed description of plant secondary metabolites is needed. The diversity of metabolites in medicinal plants is a viable way to find new metabolites that can be used in the pharmaceutical and nutraceutical industries.

The field of metabolomics has emerged because of recent improvements in analytical technologies and developments in systems biology have changed the study of phytochemicals. Metabolomics is defined as the comprehensive qualitative and quantitative analysis of low-molecular-weight metabolites present within a biological system under specific physiological conditions.^{12,13} The metabolome represents the terminal products of gene expression and therefore provides a direct biochemical representation of cellular activities and physiological states.¹² Unlike genomics and transcriptomics, metabolomics offers insights into the dynamic biochemical phenotype of organisms and enables the investigation of metabolic responses to developmental and environmental changes.^{14,15}

Plant metabolomics has emerged as an indispensable approach in medicinal plant research because it facilitates comprehensive characterization of phytochemical constituents and provides information regarding metabolic pathways, quality control, authentication, chemotaxonomic relationships, and biological activities.^{16–18} Metabolomic investigations have significantly accelerated the discovery of novel natural products and have improved our understanding of the complex biochemical interactions that govern plant physiology and ecological adaptations.¹⁷ Moreover, metabolomics has become increasingly important for studying underexplored medicinal plant species that possess the potential to yield previously unidentified metabolites with pharmacological significance.¹⁸

Several analytical platforms have been employed for metabolomic investigations, including nuclear magnetic resonance spectroscopy, gas chromatography-mass spectrometry, and liquid chromatography-mass spectrometry. Of these methods, liquid chromatography coupled with

tandem mass spectrometry (LC–MS/MS) is one of the most advanced analytical tools available for metabolites profiling.^{19,20,21} Chromatography with mass spectrometry allows for separation and detection of metabolites within complicated matrices of plants.¹⁹ LC–MS/MS also works for metabolites that thermolabile, polar, and in low concentration, which are typically hard to detect with standard analytical methods.²⁰

In the last ten years, improvements in precision and efficiency in mass spectrometry and data analysis have brought more attention to the use of LC–MS/MS in the study of medicinal plants. Fragmentation patterns produced by this technique ease the annotation of metabolites and speed up analysis. This method has been used to characterize various metabolites in plants, including flavonoids, phenolic acids, alkaloids, and terpenoids. LC–MS/MS has been used in phytochemical screening, assessment of quality in herbal products, and the discovery of biomarkers and metabolites that illustrate biological activity.

The family Malvaceae has around 244 genera and over 4,200 species, mostly in the tropics and subtropics. Diverse constituents of Malvaceae have great social, environmental and physical impacts. Malvaceae are known for their phytochemical richness. Many Malvaceae contain secondary metabolites like phenolic compounds, flavonoids, terpenoids, steroids, and tannins that display a wide range of biological activities. Despite the work that has been done to describe the phytochemicals of economically important Malvaceae, many species have still not been studied for their chemical diversity and metabolomic profiles.

Eriolaena quinquelocularis (Wight & Arn.) Drury is a medium-sized deciduous tree belonging to the family Malvaceae and is distributed mainly in tropical dry deciduous forests of the Indian subcontinent. The species possesses ecological significance and contributes to the floristic diversity of Indian forest ecosystems. However, compared with several other medicinally important members of Malvaceae, scientific information regarding its phytochemical composition remains extremely limited. Early research on the species has proposed the existence of a number of secondary metabolite classes, signifying it could be a good candidate of significant biologically natural products. However, further characterization on its metabolite composition utilizing modern analytical techniques is currently absent.

To fully realize the biochemical variety and research potential of understudied plants, their metabolites must be studied and characterized. Understanding the metabolites in plants can provide information about their chemotaxonomy and significance. Additionally, characterizing a plant's metabolites can help research the biological activities and conservation of that species. Because of the scant information available on *Eriolaena quinquelocularis* (Wight & Arn.) Drury's phytochemicals, this research was conducted to perform LC–MS/MS metabolite profiling on *E. quinquelocularis* leaf extract. The findings of the present investigation are expected to provide fundamental insights into the metabolite composition of this underexplored species and establish a scientific foundation for future phytochemical, pharmacological, and biotechnological studies.

2. Materials and Methods

2.1. Chemical

LC–MS-grade methanol, acetonitrile, formic acid, and other analytical-grade chemicals and solvents used for sample preparation and chromatographic analysis were procured from Merck India Pvt. Ltd. (Mumbai, India). Ultrapure water obtained from a Milli-Q purification system (Millipore, USA) was used throughout the study.

2.2. Plant Materials

The plant material of *Eriolaena quinquelocularis* (Wight & Arn.) Drury used in this study was collected from Ramshej, Nashik District, Maharashtra, India, in accordance with applicable local and national guidelines governing the collection of plant material for scientific research. The plant material was collected from a naturally occurring population, and only the required leaf material was collected to minimize disturbance to the plant population. The species was taxonomically authenticated by Dr. Darshan Kokate, Assistant Professor, P.G. Department of Botany, K.S.K.W. College, CIDCO, Nashik, Maharashtra, India. A voucher specimen of the collected plant material was prepared and deposited in the Departmental Herbarium for future reference. The voucher specimen is maintained under the Departmental Herbarium collection Voucher No. KSKW381.

2.3 Permissions to collect plant parts

The leaf material of *Eriolaena quinquelocularis* (Wight & Arn.) Drury used in this study was collected from a naturally occurring wild population at Ramshej Nashik, Maharashtra, India. The collection site was not within a protected or restricted area requiring a specific collection permit or licence. Accordingly, no specific collection permission or licence was required or obtained. The collection was undertaken for scientific research purposes and in accordance with applicable local and national guidelines.

2.4. Preparation of plant extract

Fresh leaves of *Eriolaena quinquelocularis* (Wight & Arn.) Drury were thoroughly washed under running tap water to remove adhering dust and debris, followed by rinsing with double-distilled water. The cleaned leaves were shade-dried at room temperature ($25 \pm 2^\circ\text{C}$) for 10–15 days until a constant weight was attained to preserve heat-sensitive phytochemicals and minimize degradation during sample preparation.^{26–27} The dried leaves were pulverized into a fine powder using a laboratory grinder and stored in airtight polyethylene containers in a cool, dry, and dark environment until extraction.²⁸

For extract preparation, 1 g of the powdered leaf material was extracted with 10 mL of LC–MS-grade methanol under continuous magnetic stirring at room temperature ($25 \pm 2^\circ\text{C}$) for 48 h. Methanol was selected as the extraction solvent because of its high efficiency in extracting a broad spectrum of polar and semi-polar phytochemicals, including phenolics, flavonoids, alkaloids, and glycosides.^{19,30} Following extraction, the mixture was centrifuged at 3,000 rpm for 15 min, and the supernatant was collected. The extract was subsequently filtered through a $0.22\ \mu\text{m}$ nylon membrane filter to remove particulate matter before LC–MS/MS analysis, thereby improving chromatographic performance and protecting the analytical column.³¹ The filtered extract was stored at 4°C until chromatographic analysis.

2.5 LC-MS/MS analysis

The metabolite profiling of *Eriolaena quinquelocularis* (Wight & Arn.) Drury leaf extract was performed using a liquid chromatography–tandem mass spectrometry (LC–MS/MS) system (SCIEX Triple Quad™ QTRAP 5500, SCIEX, Framingham, MA, USA) equipped with an electrospray ionization (ESI) source. Untargeted metabolite analysis was carried out in both positive (ESI⁺) and negative (ESI[−]) ionization modes to achieve broad metabolite coverage. Data acquisition and instrument control were performed using SCIEX OS software (Version 3.0, SCIEX, USA). Chromatographic separation was achieved on a reversed-phase C18 analytical column ($250 \times 4.6\ \text{mm}$, $5\ \mu\text{m}$ particle size). The mobile phase consisted of solvent A (water containing 0.1% formic acid, v/v) and solvent B (acetonitrile:methanol, 50:50, v/v). A gradient elution program used the following parameters: 0–2 min: 5% B; 2–15 min: 5–40% B; 15–25 min: 40–70% B; 25–35 min: 70–95% B; 35–40 min: 95% B, and was then brought back to the starting conditions for 5 min. LC–MS/MS data were processed using SCIEX OS. Tentative identifications of the metabolites were done using the precursor ion, retention time, isotope distribution, and fragmentation patterns seen in the MS/MS with the NIST 2023 mass spectral database. Metabolite identification is done using precursor mass accuracy, characteristic fragment ions, isotopic distribution, and a scoring system. This analysis and identification of metabolites were limited to high-confidence spectral matches and library scores which were considered acceptable. The mobile phase was delivered at a flow rate of $0.6\ \text{mL min}^{-1}$, the column temperature was maintained at 40°C , and the injection volume for each sample was $10\ \mu\text{L}$. Mass spectrometric detection was performed using an electrospray ionization source operated in both positive and negative ionization modes. The ion spray voltage was set at +5500 V for positive ion mode and −4500 V for negative ion mode. The source temperature was maintained at 450°C . Nitrogen was used as the nebulizer, heater, and curtain gas. The curtain gas (CUR) was maintained at 35 psi, ion source gas 1 (GS1) at 50 psi, ion source gas 2 (GS2) at 55 psi, and collision gas (CAD) was operated in the medium mode. The declustering potential (DP) was maintained at $\pm 80\ \text{V}$, while collision energy (CE) was automatically optimized for individual precursor ions during MS/MS acquisition. Data were acquired over a mass range of $m/z\ 50\text{--}1200$ with a scan rate optimized for untargeted metabolite detection.

3. Results and discussion

Using an untargeted LC-MS/MS technique with both positive and negative electrospray ionization modes, we examined the methanolic leaf extract of *Eriolaena quinquelocularis* (Wight & Arn.) Drury. The leaves of *Eriolaena quinquelocularis* (Wight & Arn.) Drury contained 46 metabolites (Table no. 01) (Figure no.01) that were tentatively identified by comparing their precursor ion m/z , retention times, and MS/MS fragmentation with the NIST 2023 spectral library. Annotated secondary metabolites were identified as four major groups of phytochemicals: fatty acids and their derivatives, phenolic acids, flavan-3-ols, and organic acids.

Among the identified metabolites, fatty acids were the most common phytochemical class. This shows that the lipid-derived components are the major phytochemicals present in *E. quinquelocularis* leaves. The extract contained several saturated fatty acids such as lauric acid, myristic acid, pentadecanoic acid, heptadecanoic acid, palmitic acid, stearic acid, arachidic acid, behenic acid, docosanoic acid, lignoceric acid, and dotriacontanoic acid. These compounds were detected with comparatively high chromatographic responses, suggesting that they are major constituents of the methanolic extract. Among them, arachidic acid exhibited the highest peak area (3.811×10^8), followed by phytanic acid (2.258×10^8), arachidic acid (2.284×10^8) in positive ion mode, palmitic acid (1.900×10^8), myristic acid (1.566×10^8), behenic acid (1.515×10^8), and eicosanoic acid (1.368×10^8). The predominance of long-chain saturated fatty acids suggests active fatty acid biosynthesis and storage metabolism within the leaf tissues.

In addition to saturated fatty acids, several biologically important unsaturated fatty acids were detected, including oleic acid, linoleic acid, palmitoleic acid, vaccenic acid, petroselinic acid, gondoic acid, eicosenoic acid, ricinoleic acid, arachidonic acid, mead acid, octadecadienoic acid, and erucic acid. Oleic acid exhibited one of the highest chromatographic responses (1.998×10^8), while vaccenic acid (1.042×10^8), petroselinic acid (1.068×10^8), eicosenoic acid (1.149×10^8), and gondoic acid (9.184×10^7) were also abundant. Unsaturated fatty acids are

well known structural components of biological membranes and are involved in plant growth, membrane fluidity, environmental adaptation, and defense responses. Their abundance in *E. quinquelocularis* indicates active lipid metabolism and may contribute to several reported biological properties of plant-derived extracts. The extract also contained branched-chain fatty acids, including phytanic acid and pristanic acid. Phytanic acid produced one of the most intense chromatographic signals in both ionization modes, whereas pristanic acid was detected with considerable abundance. Branched-chain fatty acids are comparatively uncommon constituents in higher plants and may serve as valuable chemotaxonomic markers. They may reflect unique metabolic pathways in *E. quinquelocularis* that differentiate it from the other members of Malvaceae.

In addition to lipid constituents, LC-MS/MS found several phenolic acids including gallic, caffeic, protocatechuic, vanillic, gentisic, salicylic, and p-hydroxybenzoic acids. Though they were found in lower abundance compared to fatty acids, phenolic acids are a class of specialized metabolites and are important for plant defense mechanisms and for responding to oxidative stress. Of the phenolic acids that were found, p-hydroxybenzoic acid (1.442×10^6) and gallic acid (1.011×10^6) were the most abundant and showed the highest chromatographic response, while the remaining phenolic acids were gentisic, protocatechuic, vanillic, and caffeic acids.

Catechin and epicatechin, two interesting flavan-3-ols with precursor ions at m/z 289, were also detected. These flavonoids are widely distributed polyphenolic compounds in higher plants, and often contribute to the antioxidant capacity of plant extracts. Their chromatographic peak areas were relatively low compared with those of fatty acids. However, the detection of catechin and epicatechin demonstrates that *E. quinquelocularis* possesses multiple classes of secondary metabolites with diverse biosynthetic origins.

The analysis picked out a few smaller organic acids, such as fumaric acid, maleic acid, malic acid, succinic acid, azelaic acid, suberic acid, dodecanedioic acid, terephthalic acid, isophthalic acid, and phthalic acid. Organic acids are important for central carbon metabolism, tricarboxylic acid cycle, and cellular respiration, and some dicarboxylic acids are involved in plant signaling and defense. Their presence additionally denotes the metabolic sophistication of the species studied.

Metabolite profiling shows that *E. quinquelocularis* leaves contain long-chain fatty acids, phenolic acids, flavonoids, and organic acids. The multiple forms of saturated and unsaturated fatty acids found in the leaves suggest that lipid metabolism is important for *E. quinquelocularis*. Additionally, the detection of phenolic acids and flavan-3-ols indicates that *E. quinquelocularis* leaves may contain a diverse array of secondary metabolites which may have important ecological roles and may exhibit some biological activity.

To the best of our knowledge, this represents the first comprehensive LC–MS/MS-based metabolite profile of *Eriolaena quinquelocularis* leaves. The metabolite dataset generated in the present investigation provides valuable baseline information for future phytochemical characterization, chemotaxonomic studies, metabolomic comparisons within Malvaceae, and investigations into the biological properties of this underexplored medicinal tree species.

Table.No.01

Sr. No.	Metabolite	Molecular Formula	Retention Time	Mode +/-	Molecular Weight (g/mol)	Chemical Class	Major Reported Biological Activities	Reference
1.	Palmitic acid	C ₁₆ H ₃₂ O ₂	32.00	+	256.42	Saturated fatty acid	Membrane constituent; lipid metabolism; cell signaling; antimicrobial; immunomodulatory; inflammation-associated fatty acid	30,31,32
2.	Myristic acid	C ₁₄ H ₂₈ O ₂	31.93	+	228.37	Saturated fatty acid	Antimicrobial; anti-inflammatory; lipid metabolism; membrane constituent; protein myristoylation	33,34
3.	Lauric acid	C ₁₂ H ₂₄ O ₂	33.32	+	200.32	Saturated fatty acid	Antibacterial; antifungal; antiviral; anti-inflammatory; membrane-disrupting antimicrobial agent	35,36,37,38
4.	Linoleic acid	C ₁₈ H ₃₂ O ₂	33.00	+	280.45	Polyunsaturated fatty acid	Antioxidant; anti-inflammatory; antimicrobial; wound healing; skin barrier repair; cardioprotective	39,40,41,42
5.	Behenic acid	C ₂₂ H ₄₄ O ₂	33.56	+	340.58	Saturated fatty acid	Emollient; membrane structural lipid; skin-conditioning agent; lipid metabolism; pharmaceutical and cosmetic excipient.	43,44,45
6.	Palmitoleic acid	C ₁₆ H ₃₀ O ₂	32.63	+	254.41	Monounsaturated fatty acid	Anti-inflammatory; antimicrobial; metabolic regulator; insulin-sensitizing; lipokine; cardioprotective	46,47,48,49
7.	Eicosenoic acid	C ₂₀ H ₃₈ O ₂	32.55	+	310.52	Monounsaturated fatty acid	Anti-inflammatory; membrane structural lipid; lipid metabolism; cardioprotective; antimicrobial	50,51,52
8.	Docosanoic acid (Behenic acid)	C ₂₂ H ₄₄ O ₂	33.56	+	340.58	Saturated fatty acid	Lipid metabolism, antimicrobial	53,54
9.	Phytanic acid	C ₂₀ H ₄₀ O ₂	32.52	+	312.53	Branched-chain fatty acid	Lipid metabolism; cellular signaling; PPAR-α/RXR activation; regulation of peroxisomal β-oxidation; energy homeostasis	55,56
10.	Heptadecanoic acid	C ₁₇ H ₃₄ O ₂	33.37	+	270.45	Saturated fatty acid	Anti-inflammatory; biomarker of dairy fat intake; lipid metabolism; cardiometabolic health biomarker; membrane structural lipid	57,58,53
11.	Eicosanoic acid	C ₂₀ H ₄₀ O ₂	32.46	+	312.53	Saturated fatty acid	Membrane structural lipid; lipid metabolism;	59,60

Sr. No.	Metabolite	Molecular Formula	Retention Time	Mode +/-	Molecular Weight (g/mol)	Chemical Class	Major Reported Biological Activities	Reference
1.	Palmitic acid	C ₁₆ H ₃₂ O ₂	32.00	+	256.42	Saturated fatty acid	Membrane constituent; lipid metabolism; cell signaling; antimicrobial; immunomodulatory; inflammation-associated fatty acid	30,31,32
							antimicrobial; energy storage; skin-conditioning agent	
12.	Gondoic acid (11-Eicosenoic acid)	C ₂₀ H ₃₈ O ₂	32.55	+	310.52	Monounsaturated fatty acid	Lipid metabolism; anti-inflammatory; membrane structural lipid; antimicrobial; cardioprotective	61,62,63
13.	Ricinoleic acid	C ₁₈ H ₃₄ O ₃	29.38	+	298.46	Hydroxy fatty acid	Anti-inflammatory; antimicrobial; analgesic; wound healing; antioxidant; antinociceptive	64,65
14.	Mead acid	C ₂₀ H ₃₄ O ₂	33.87	+	306.49	Polyunsaturated fatty acid	Anti-inflammatory; immune regulation; lipid metabolism; regulation of eicosanoid biosynthesis; antiproliferative activity	66,67,68
15.	Octadecadienoic acid (Linoleic acid)	C ₁₈ H ₃₂ O ₂	32.66	+	280.45	Polyunsaturated fatty acid (PUFA)	Antioxidant; anti-inflammatory; antimicrobial; wound healing; cardioprotective; hypocholesterolemic	69,70
16.	Arachidonic acid	C ₂₀ H ₃₂ O ₂	33.89	+	304.47	Polyunsaturated fatty acid (ω-6)	Precursor of eicosanoids; inflammatory signaling; immune modulation; membrane phospholipid constituent; cell proliferation	71,72,73
17.	Fumaric acid	C ₄ H ₄ O ₄	33.86	+	116.07	Dicarboxylic acid (Organic acid)	Antioxidant; antimicrobial; anti-inflammatory; immunomodulatory; tricarboxylic acid (TCA) cycle intermediate	74,75
18.	Maleic acid	C ₄ H ₄ O ₄	33.86	+	116.07	Dicarboxylic acid (Organic acid)	Antimicrobial; metabolic intermediate; preservative; pH regulator; food acidulant	76,77,78
19.	Petroselinic acid	C ₁₈ H ₃₄ O ₂	32.48	+	282.46	Monounsaturated fatty acid	Anti-inflammatory; antimicrobial; skin-conditioning agent; cosmetic emollient; lipid metabolism	79,80
20.	Pristanic acid	C ₁₉ H ₃₈ O ₂	31.70	+	298.50	Branched-chain fatty acid	Regulates lipid metabolism;	81,82,83

Sr. No.	Metabolite	Molecular Formula	Retention Time	Mode +/-	Molecular Weight (g/mol)	Chemical Class	Major Reported Biological Activities	Reference
1.	Palmitic acid	C ₁₆ H ₃₂ O ₂	32.00	+	256.42	Saturated fatty acid	Membrane constituent; lipid metabolism; cell signaling; antimicrobial; immunomodulatory; inflammation-associated fatty acid	30,31,32
							activates PPAR-α; promotes peroxisomal β-oxidation; cellular signaling	
21.	Arachidic acid	C ₂₀ H ₄₀ O ₂	32.54	+	312.53	Saturated fatty acid	Antimicrobial; anti-inflammatory; membrane structural lipid; lipid metabolism; energy storage	84,85
22.	Azelaic acid	C ₉ H ₁₆ O ₄	22.67	+	188.22	Dicarboxylic acid	Antioxidant; antibacterial; anti-inflammatory; anti-acne; tyrosinase inhibitor; depigmenting agent	86,87
23.	Vaccenic acid	C ₁₈ H ₃₄ O ₂	32.49	+	282.46	Monounsaturated fatty acid	Anti-inflammatory; cardioprotective; antimicrobial; lipid metabolism regulator; improves insulin sensitivity	88,89,90
24.	Oleic acid	C ₁₈ H ₃₄ O ₂	32.49	+	282.46	Monounsaturated fatty acid (MUFA)	Anti-inflammatory; antimicrobial; cardioprotective; hypolipidemic; membrane constituent; antioxidant potential	91,92,93,94
25.	Vanillic acid	C ₈ H ₈ O ₄	9.86	+	168.15	Phenolic acid (Hydroxybenzoic acid derivative)	Antioxidant; anti-inflammatory; antimicrobial; hepatoprotective; neuroprotective; anticancer	95,96,97
26.	Terephthalic acid	C ₈ H ₆ O ₄	32.04	+	166.13	Aromatic dicarboxylic acid	Intermediate in aromatic metabolism; environmental metabolite; limited reported biological activity in plants	98,99,100,101
27.	Suberic acid	C ₈ H ₁₄ O ₄	19.74	+	174.19	Dicarboxylic acid	Fatty acid metabolism intermediate; biomarker of lipid oxidation; antioxidant potential	102,103
28.	Caffeic acid	C ₉ H ₈ O ₄	3.62	+	180.16	Hydroxycinnamic acid (Phenolic acid)	Potent antioxidant; anti-inflammatory; antimicrobial; anticancer; hepatoprotective; antidiabetic	104,105,106
29.	Isophthalic acid	C ₈ H ₆ O ₄	31.59	+	166.13	Aromatic dicarboxylic acid	Intermediate in aromatic compound	107,108,109

Sr. No.	Metabolite	Molecular Formula	Retention Time	Mode +/-	Molecular Weight (g/mol)	Chemical Class	Major Reported Biological Activities	Reference
1.	Palmitic acid	C ₁₆ H ₃₂ O ₂	32.00	+	256.42	Saturated fatty acid	Membrane constituent; lipid metabolism; cell signaling; antimicrobial; immunomodulatory; inflammation-associated fatty acid	30,31,32
							metabolism; limited biological activity reported	
30.	Phthalic acid	C ₈ H ₆ O ₄	32.82	+	166.13	Aromatic dicarboxylic acid	Environmental metabolite; intermediate in aromatic compound degradation; reported antimicrobial activity in some microbial metabolites; limited biological role in plants	110,111
31.	Stearic acid	C ₁₈ H ₃₆ O ₂	30.02	+	284.48	Saturated fatty acid	Antimicrobial; anti-inflammatory; membrane structural lipid; energy storage; lipid metabolism	112,113,114
32.	Salicylic acid	C ₇ H ₆ O ₃	34.61	+	138.12	Phenolic acid (Plant hormone)	Plant defense signaling; antioxidant; anti-inflammatory; antimicrobial; systemic acquired resistance (SAR) inducer	115,116
33.	Malic acid	C ₄ H ₆ O ₅	33.51	+	134.09	Organic acid (TCA cycle intermediate)	Antioxidant; antimicrobial; metabolic intermediate; osmotic regulation; energy metabolism	117,118,119, 120
34.	Dodecanedioic acid	C ₁₂ H ₂₂ O ₄	10.94	+	230.30	Long-chain dicarboxylic acid	Lipid metabolism intermediate; ω-oxidation metabolite; antimicrobial activity; energy metabolism	100,121
35.	Dotriacontanoic acid	C ₃₂ H ₆₄ O ₂	32.87	+	480.85	Very long-chain saturated fatty acid	Cuticular wax constituent; membrane protection; abiotic stress adaptation; reported antimicrobial activity	122,123
36.	Pentadecanoic acid	C ₁₅ H ₃₀ O ₂	33.51	+	242.40	Saturated fatty acid	Anti-inflammatory; antimicrobial; biomarker of dairy-derived fatty acids; lipid metabolism regulator; potential cardiometabolic benefits	55,124,125
37.	Erucic acid	C ₂₂ H ₄₂ O ₂	33.07	+	338.57	Monounsaturated fatty acid	Anti-inflammatory; antimicrobial;	59,126,127

Sr. No.	Metabolite	Molecular Formula	Retention Time	Mode +/-	Molecular Weight (g/mol)	Chemical Class	Major Reported Biological Activities	Reference
1.	Palmitic acid	C ₁₆ H ₃₂ O ₂	32.00	+	256.42	Saturated fatty acid	Membrane constituent; lipid metabolism; cell signaling; antimicrobial; immunomodulatory; inflammation-associated fatty acid	30,31,32
							membrane lipid constituent; lipid metabolism	
38.	Gallic acid	C ₇ H ₆ O ₅	34.45	-	170.12	Phenolic acid (Trihydroxybenzoic acid)	Potent antioxidant; antimicrobial; anti-inflammatory; anticancer; antidiabetic; hepatoprotective	128,129,130
39.	Protocatechuic acid	C ₇ H ₆ O ₄	34.58	-	154.12	Phenolic acid (Dihydroxybenzoic acid)	Potent antioxidant; anti-inflammatory; antimicrobial; anticancer; cardioprotective; hepatoprotective	131,132
40.	p-Hydroxybenzoic acid	C ₇ H ₆ O ₃	33.44	-	138.12	Phenolic acid (Hydroxybenzoic acid derivative)	Antioxidant; antimicrobial; anti-inflammatory; antifungal; allelopathic activity	133,134, 135
41.	Gentisic acid	C ₇ H ₆ O ₄	34.58	-	154.12	Phenolic acid (Dihydroxybenzoic acid)	Antioxidant; anti-inflammatory; antimicrobial; free radical scavenger; cytoprotective	136,137
42.	Catechin	C ₁₅ H ₁₄ O ₆	33.93	-	290.27	Flavan-3-ol (Flavonoid)	Potent antioxidant; anti-inflammatory; antimicrobial; anticancer; cardioprotective; antidiabetic	138,139,140
43.	Epicatechin	C ₁₅ H ₁₄ O ₆	33.91	-	290.27	Flavan-3-ol (Flavonoid)	Potent antioxidant; cardioprotective; anti-inflammatory; neuroprotective; antimicrobial; antidiabetic	141,142
44.	Dihydrosterculic acid	C ₁₉ H ₃₆ O ₂	31.63	-	296.49	Cyclopropane fatty acid	Membrane structural lipid; lipid metabolism; chemotaxonomic marker; reported antimicrobial activity	143,144,145
45.	Lignoceric acid	C ₂₄ H ₄₈ O ₂	32.78	-	368.64	Very long-chain saturated fatty acid	Membrane structural lipid; cuticular wax constituent; abiotic stress adaptation; energy storage; reported antimicrobial activity	146,147
46.	Succinic acid	C ₄ H ₆ O ₄	33.76	-	118.09	Organic acid (Dicarboxylic acid)	TCA cycle intermediate; metabolic regulator; immunomodulatory signaling molecule; antimicrobial	148,149,150

Sr. No.	Metabolite	Molecular Formula	Retention Time	Mode +/-	Molecular Weight (g/mol)	Chemical Class	Major Reported Biological Activities	Reference
1.	Palmitic acid	C ₁₆ H ₃₂ O ₂	32.00	+	256.42	Saturated fatty acid	Membrane constituent; lipid metabolism; cell signaling; antimicrobial; immunomodulatory; inflammation-associated fatty acid	30.31.32
							activity; cellular energy metabolism	

4. Conclusion

The present study provides the first comprehensive untargeted LC–MS/MS metabolite profile of the methanolic leaf extract of *Eriolaena quinquelocularis* (Wight & Arn.) Drury. A total of 46 metabolites were successfully identified using electrospray ionization in both positive and negative ionization modes. These metabolites represent a chemically diverse repertoire comprising saturated, monounsaturated, polyunsaturated, branched-chain, cyclopropane, and very long-chain fatty acids, together with phenolic acids, flavonoids, and organic acids. Among the major constituents identified were palmitic acid, arachidic acid, oleic acid, vaccenic acid, stearic acid, phytanic acid, behenic acid, eicosanoic acid, petroselinic acid, lignoceric acid, catechin, epicatechin, gallic acid, caffeic acid, protocatechuic acid, gentisic acid, salicylic acid, vanillic acid, malic acid, succinic acid, fumaric acid, and several other biologically important metabolites. The pharmacological properties of the compounds that have been discovered include antioxidant, antimicrobial, anti-inflammatory, cardioprotective, hepatoprotective, neuroprotective, antidiabetic, immunomodulatory, and anticancer activities. The multiple varieties of bioactive metabolites suggest that the therapeutic potential of *E. quinquelocularis* is likely due to the interaction or cooperation of its phytochemical constituents and not due to the individual activity of single compounds. Fatty acids, along with phenolic acids and flavonoids, are indicative of the natural metabolites contained within the species of valuably occurring pharmaceuticals and nutraceuticals.

This study broadens the known metabolites of *E. quinquelocularis*, a little known medicinal tree in the Malvaceae family. From a taxonomic standpoint, it offers a method of establishing a chemical fingerprint from which a plant can be reliably identified. This study also serves to standardize phytochemicals and perform quality control assessments on other plant derived material. The dataset of the metabolites generated in this study will serve as an excellent baseline for other studies on comparative metabolomics and chemotaxonomy of the genus and related taxa. The results overall support that *E. quinquelocularis* is a new potential natural source of varied bioactive metabolites and give a solid scientific support for directing its future use in the fields of pharmaceutical, nutraceutical, functional food and natural products drug discovery research.

Declarations

Consent for publication

The author declares that the work has consent for publication.

Funding support

The author declares that they have no funding support for this Study.

CRedit authorship contribution statement

Saurav Gaikwad: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft. Ramakant Patil: Supervision, Validation, Project administration, Resources, Funding acquisition, Writing – review & editing. Darshan Kokate: Software, Data curation, Investigation, Visualization, Writing – review & editing.

Data Availability Statement

The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors sincerely thank all those who contributed directly or indirectly to the successful completion of this study. The authors also acknowledge the valuable support and cooperation received during the course of this research.

The authors are grateful to the Principals and Heads of their respective colleges and departments for providing necessary facilities.

Ethics, Consent to Participate, and Consent to Publish declarations: not applicable.

References

1. Atanasov AG, Zotchev SB, Dirsch VM, Supuran CT. Natural products in drug discovery: advances and opportunities. *Nat Rev Drug Discov*. 2021;20:200–16. <https://doi.org/10.1038/s41573-020-00114-z>.
2. Sumner LW, Mendes P, Dixon RA. Plant metabolomics: large-scale phytochemistry in the functional genomics era. *Phytochemistry*. 2003;62:817–36. [https://doi.org/10.1016/S0031-9422\(02\)00708-2](https://doi.org/10.1016/S0031-9422(02)00708-2).
3. Fiehn O. Metabolomics—the link between genotypes and phenotypes. *Plant Mol Biol*. 2002;48:155–71. <https://doi.org/10.1023/A:1013713905833>.
4. Hall RD. Plant metabolomics: from holistic hope to hype to hot topic. *New Phytol*. 2006;169:453–68. <https://doi.org/10.1111/j.1469-8137.2005.01632.x>.
5. Wink M. Biochemistry of plant secondary metabolism. *Annu Plant Rev*. 2010;40:1–19. [10.1002/9781444320503.ch1](https://doi.org/10.1002/9781444320503.ch1).
6. Dixon RA, Strack D. Phytochemistry meets genome analysis. *Phytochemistry*. 2003;62:815–6. [https://doi.org/10.1016/s0031-9422\(02\)00712-4](https://doi.org/10.1016/s0031-9422(02)00712-4).
7. Saito K, Matsuda F. Metabolomics for functional genomics and systems biology. *Annu Rev Plant Biol*. 2010;61:463–89. <https://doi.org/10.1146/annurev.arplant.043008.092035>.
8. Zhong JJ. 3.27 Plant Secondary Metabolites. In: *Comprehensive Biotechnology (Third Edition) 2011 (Vol. 3)*. Elsevier. <https://doi.org/10.1016/B978-0-444-64046-8.00169-5>
9. Bino RJ, Hall RD, Fiehn O, et al. Potential of metabolomics as a functional genomics tool. *Trends Plant Sci*. 2004;9:418–25. <https://doi.org/10.1016/j.tplants.2004.07.004>.
10. Okazaki Y, Saito K. Integrated metabolomics and phytochemical genomics approaches for studies on rice. *GigaScience*. 2016;5(1):s13742–016. <https://doi.org/10.1186/s13742-016-0116-7>.
11. Penumallu NR, Abass S, Parveen R, Ahmed S. Metabolomics in Medicinal Plants: Unraveling the Therapeutic Potential of Natural Compounds. In: *Ethnopharmacology and OMICS Advances in Medicinal Plants Volume 1: Uncovering Diversity and Ethnopharmacological Aspects 2024 Oct 10 (pp. 285–312)*. https://doi.org/10.1007/978-981-97-2367-6_15
12. Fiehn O. Combining genomics, metabolome analysis and biochemical modelling to understand metabolic networks. *Comp Funct Genomics*. 2001;2:155–68. <https://doi.org/10.1002/cfg.82>.
13. Sumner LW, Amberg A, Barrett D, Beale MH, Beger R, Daykin CA, Fan TW, Fiehn O, Goodacre R, Griffin JL, Hankemeier T. Proposed minimum reporting standards for chemical analysis: chemical analysis working group (CAWG) metabolomics standards initiative (MSI). *Metabolomics*. 2007;3(3):211–21. <https://doi.org/10.1007/s11306-007-0082-2>.
14. Oliver SG, Winson MK, Kell DB, Baganz F. Systematic functional analysis of the yeast genome. *Trends Biotechnol*. 1998;16:373–8. [https://doi.org/10.1016/S0167-7799\(98\)01214-1](https://doi.org/10.1016/S0167-7799(98)01214-1).
15. Lv G, Hu D, Zhao J, Li S. Quality control of sweet medicines based on gas chromatography-mass spectrometry. *Drug Discoveries Ther*. 2015;9(2):94–106. <https://doi.org/10.5582/ddt.2015.01020>.
16. Waris M, Kocak E, Gonulalan EM, Demirezer LO, Kir S, Nemutlu E. Metabolomics analysis insight into medicinal plant science. *TRAC Trends Anal Chem*. 2022;157:116795. <https://doi.org/10.1016/j.trac.2022.116795>.
17. Patel MK, Pandey S, Kumar M, Haque MI, Pal S, Yadav NS. Plants metabolome study: Emerging tools and techniques. *Plants*. 2021;10(11):2409. <https://doi.org/10.3390/plants10112409>.
18. Scossa F, Alseekh S, Fernie AR. Integrating multi-omics data for crop improvement. *J Plant Physiol*. 2021;257:153352. <https://doi.org/10.1016/j.jplph.2020.153352>.
19. Theodoridis G, Gika HG, Wilson ID. LC-MS-based methodology for global metabolite profiling in metabonomics/metabolomics. *TRAC Trends Anal Chem*. 2008;27(3):251–60. <https://doi.org/10.1016/j.trac.2008.01.008>.

20. Lu W, Bennett BD, Rabinowitz JD. Analytical strategies for LC–MS-based targeted metabolomics. *J Chromatogr B*. 2008;871(2):236–42. <https://doi.org/10.1016/j.jchromb.2008.04.031>.
21. Gautam G, Parveen R, Ahmad S. LC–MS-based metabolomics of medicinal plants. *Omics Studies of Medicinal Plants*. Boca Raton: CRC; 2023. pp. 157–80. <https://doi.org/10.1201/9781003179139>.
22. Dunn WB, Goodacre R, Neyses L, Mamas M. Integration of metabolomics in heart disease and diabetes research: current achievements and future outlook. *Bioanalysis*. 2011;3(19):2205–22. <https://doi.org/10.4155/bio.11.223>.
23. Wolfender JL, Glauser G, Boccard J, Rudaz S. MS-based plant metabolomic approaches for biomarker discovery. *Nat Prod Commun*. 2009;4(10):1934578X0900401019. <https://doi.org/10.1177/1934578X0900401019>.
24. Austin DF. Flowering Plant Families of the World, Revised. *Economic Botany*. 2007;61(3):310-1. [https://doi.org/10.1663/0013-0001\(2007\)61\[310:FPFOTW\]2.0.CO;2](https://doi.org/10.1663/0013-0001(2007)61[310:FPFOTW]2.0.CO;2).
25. Bachheti RK, Bachheti A, Husen A, editors. *Phenolic Compounds from Medicinal Plants: Pharmaceutical and Health Benefits*. CRC; 2026 May. p. 19.
26. Shaikh S, Pande V, Alte MA, Tawale MS, Hardas MD. Phytochemical Constituents and Active Principles. *Herbal Nutraceuticals and Functional Applications of Celosia argentea and Allied Botanicals*. 2026;4:51. <https://doi.org/10.70593/978-93-7185-768-0>
27. Patra JK, Das G, Lee S, Kang SS, Shin HS. Selected commercial plants: A review of extraction and isolation of bioactive compounds and their pharmacological market value. *Trends Food Sci Technol*. 2018;82:89–109. <https://doi.org/10.1016/j.tifs.2018.10.001>.
28. Dai J, Mumper RJ. Plant phenolics: extraction, analysis and their antioxidant and anticancer properties. *Molecules*. 2010;15(10):7313–52. <https://doi.org/10.3390/molecules15107313>.
29. Yuan B, Dinssa FF, Simon JE, Wu Q. Simultaneous quantification of polyphenols, glycoalkaloids and saponins in African nightshade leaves using ultra-high performance liquid chromatography tandem mass spectrometry with acid assisted hydrolysis and multivariate analysis. *Food Chem*. 2020;312:126030. <https://doi.org/10.1016/j.foodchem.2019.126030>.
30. Carta G, Murru E, Banni S, Manca C. Palmitic acid: physiological role, metabolism and nutritional implications. *Front Physiol*. 2017;8:902. <https://doi.org/10.3389/fphys.2017.00902>.
31. Korbecki J, Bajdak-Rusinek K. The effect of palmitic acid on inflammatory response in macrophages: an overview of molecular mechanisms. *Inflamm Res*. 2019;68(11):915. <https://doi.org/10.1007/s00011-019-01273-5>.
32. Mancini A, Imperlini E, Nigro E, Montagnese C, Daniele A, Orrù S, Buono P. Biological and nutritional properties of palm oil and palmitic acid: effects on health. *Molecules*. 2015;20(9):17339–61. <https://doi.org/10.3390/molecules200917339>.
33. Fatima S, Hu X, Gong RH, Huang C, Chen M, Wong HL, Bian Z, Kwan HY. Palmitic acid is an intracellular signaling molecule involved in disease development. *Cell Mol Life Sci*. 2019;76(13):2547. <https://doi.org/10.1007/s00018-019-03092-7>.
34. Rioux V, Legrand P. Saturated fatty acids: simple molecular structures with complex cellular functions. *Curr Opin Clin Nutr Metabolic Care*. 2007;10(6):752–8. <https://doi.org/10.1097/MCO.0b013e3282f01a75>.
35. Sinclair AJ, Attar-Bashi NM, Li D. What is the role of α -linolenic acid for mammals? *Lipids*. 2002;37(12):1113–23. <https://doi.org/10.1007/s11745-002-1008-x>.
36. Desbois AP, Smith VJ. Antibacterial free fatty acids: activities, mechanisms of action and biotechnological potential. *Appl Microbiol Biotechnol*. 2010;85(6):1629–42. <https://doi.org/10.1007/s00253-009-2355-3>.
37. Resh MD. Fatty acylation of proteins: new insights into membrane targeting of myristoylated and palmitoylated proteins. *Biochimica et Biophysica Acta (BBA)-Molecular Cell Research*. 1999;1451(1):1–6. [https://doi.org/10.1016/S0167-4889\(99\)00075-0](https://doi.org/10.1016/S0167-4889(99)00075-0)
38. Dayrit FM. The properties of lauric acid and their significance in coconut oil. *J Am Oil Chem Soc*. 2015;92(1):1–5. <https://doi.org/10.1007/s11746-014-2562-7>.
39. Kabara JJ, Swieczkowski DM, Conley AJ, Truant JP. Fatty acids and derivatives as antimicrobial agents. *Antimicrob Agents Chemother*. 1972;2(1):23–8. <https://doi.org/10.1128/aac.2.1.23>.
40. Preuss HG, Echard B, Enig M, Brook I, Elliott TB. Minimum inhibitory concentrations of herbal essential oils and monolaurin for gram-positive and gram-negative bacteria. *Mol Cell Biochem*. 2005;272(1):29–34. <https://doi.org/10.1007/s11010-005-6604-1>.
41. Whelan J, Fritsche K. Linoleic acid. *Advances in nutrition*. 2013;4(3):311–2. <https://doi.org/10.3945/an.113.003772>
42. Belury MA. Dietary conjugated linoleic acid in health: physiological effects and mechanisms of action. *Annu Rev Nutr*. 2002;22(1):505–31. <https://doi.org/10.1146/annurev.nutr.22.021302.121842>.
43. Ziboh VA, Miller CC, Cho Y. Metabolism of polyunsaturated fatty acids by skin epidermal enzymes: generation of antiinflammatory and antiproliferative metabolites. *Am J Clin Nutr*. 2000;71(1):361. <https://doi.org/10.1093/ajcn/71.1.361S>. S-6S.
44. Chen M, Vijay V, Shi Q, Liu Z, Fang H, Tong W. FDA-approved drug labeling for the study of drug-induced liver injury. *Drug Discovery Today*. 2011;16(15–16):697–703. <https://doi.org/10.1016/j.drudis.2011.05.007>.

45. Cater NB, Denke MA. Behenic acid is a cholesterol-raising saturated fatty acid in humans. *Am J Clin Nutr.* 2001;73(1):41–4. <https://doi.org/10.1093/ajcn/73.1.41>.
46. Moore EM, Wagner C, Komarnytsky S. The enigma of bioactivity and toxicity of botanical oils for skin care. *Front Pharmacol.* 2020;11:785. <https://doi.org/10.3389/fphar.2020.00785>.
47. Chu CC, Nyam KL. Application of seed oils and its bioactive compounds in sunscreen formulations. *J Am Oil Chem Soc.* 2021;98(7):713–26. <https://doi.org/10.1002/aocs.12491>.
48. Cao H, Gerhold K, Mayers JR, Wiest MM, Watkins SM, Hotamisligil GS. Identification of a lipokine, a lipid hormone linking adipose tissue to systemic metabolism. *Cell.* 2008;134(6):933–44. <https://doi.org/10.1016/j.cell.2008.07.048>.
49. Frigolet ME, Gutiérrez-Aguilar R. The role of the novel lipokine palmitoleic acid in health and disease. *Adv Nutr.* 2017;8(1):S173–81. <https://doi.org/10.3945/an.115.011130>.
50. Shramko VS, Polonskaya YV, Kashtanova EV, Stakhneva EM, Ragino YI. The short overview on the relevance of fatty acids for human cardiovascular disorders. *Biomolecules.* 2020;10(8):1127. <https://doi.org/10.3390/biom10081127>.
51. Ntambi JM, Miyazaki M. Regulation of stearoyl-CoA desaturases and role in metabolism. *Prog Lipid Res.* 2004;43(2):91–104. [https://doi.org/10.1016/S0163-7827\(03\)00039-0](https://doi.org/10.1016/S0163-7827(03)00039-0).
52. Wanders RJ, Komen J, Kemp S. Fatty acid omega-oxidation as a rescue pathway for fatty acid oxidation disorders in humans. *FEBS J.* 2011;278(2):182–94. <https://doi.org/10.1111/j.1742-4658.2010.07947.x>.
53. Jenkins B, West JA, Koulman A. A review of odd-chain fatty acid metabolism and the role of pentadecanoic acid (C15: 0) and heptadecanoic acid (C17: 0) in health and disease. *Molecules.* 2015;20(2):2425–44. <https://doi.org/10.3390/molecules20022425>.
54. Imamura F, Fretts A, Marklund M, Ardisson Korat AV, Yang WS, Lankinen M, Qureshi W, Helmer C, Chen TA, Wong K, Bassett JK. Fatty acid biomarkers of dairy fat consumption and incidence of type 2 diabetes: a pooled analysis of prospective cohort studies. *PLoS Med.* 2018;15(10):e1002670. <https://doi.org/10.1371/journal.pmed.1002670>.
55. Venn-Watson S, Lumpkin R, Dennis EA. Efficacy of dietary odd-chain saturated fatty acid pentadecanoic acid parallels broad associated health benefits in humans: could it be essential? *Sci Rep.* 2020;10(1):8161. <https://doi.org/10.1038/s41598-020-64960-y>.
56. Zomer AW, van der Burg B, Jansen GA, Wanders RJA, Poll-The BT, van der Saag PT. Pristanic acid and phytanic acid are natural ligands for the nuclear receptor peroxisome proliferator-activated receptor alpha (PPARα). *J Lipid Res.* 2000;41(11):1801–7. [https://doi.org/10.1016/S0022-2275\(20\)31973-8](https://doi.org/10.1016/S0022-2275(20)31973-8).
57. Rustan AC, Drevon CA. Fatty acids: structures and properties. *Encyclopedia life Sci.* 2005;1(1):1–7. <https://doi.org/10.1038/npg.els.0003894>.
58. Lang T, Halemani ND, Rammner B. Interplay between lipids and the proteinaceous membrane fusion machinery. *Prog Lipid Res.* 2008;47(6):461–9. <https://doi.org/10.1016/j.plipres.2008.08.002>.
59. Akoh CC. Food lipids: chemistry, nutrition, and biotechnology. CRC; 2017 Mar. p. 16. <https://doi.org/10.1201/9781315151854>.
60. Beare-Rogers JL, Dieffenbacher A, Holm JV. Lexicon of lipid nutrition (IUPAC Technical Report). *Pure and applied chemistry.* 2001;73(4):685–744. <https://doi.org/10.1351/pac200173040685>.
61. Fan G, Li Y, Liu Y, Suo X, Jia Y, Yang X. Gondoic acid alleviates LPS-induced Kupffer cells inflammation by inhibiting ROS production and PKCθ/ERK/STAT3 signaling pathway. *Int Immunopharmacol.* 2022;111:109171. <https://doi.org/10.1016/j.intimp.2022.109171>.
62. Sato K, Yano J, Kawada I, Kawano M, Kaneko F, Suzuki M. Polymorphic behavior of gondoic acid and phase behavior of its binary mixtures with asclepic acid and oleic acid. *J Am Oil Chem Soc.* 1997;74(9):1153–9. <https://doi.org/10.1007/s11746-997-0039-7>.
63. Emelianova AA, Kuzmin DV, Panteleev PV, Sorokin M, Buzdin AA, Ovchinnikova TV. Anticancer activity of the goat antimicrobial peptide ChMAP-28. *Front Pharmacol.* 2018;9:1501. <https://doi.org/10.3389/fphar.2018.01501>.
64. Vieira C, Evangelista S, Cirillo R, Lippi A, Maggi CA, Manzini S. Effect of ricinoleic acid in acute and subchronic experimental models of inflammation. *Mediat Inflamm.* 2000;9(5):223–8. <https://doi.org/10.1080/09629350020025737>.
65. Rios JL, Recio MC. Medicinal plants and antimicrobial activity. *J Ethnopharmacol.* 2005;100(1–2):80–. <https://doi.org/10.1016/j.jep.2005.04.025>. 4.
66. Spector AA, Kim HY. Discovery of essential fatty acids. *J Lipid Res.* 2015;56(1):11–21. <https://doi.org/10.1194/jlr.R055095>.
67. Kawashima H, Yoshizawa K. The physiological and pathological properties of Mead acid, an endogenous multifunctional n-9 polyunsaturated fatty acid. *Lipids Health Dis.* 2023;22(1):172. <https://doi.org/10.1186/s12944-023-01937-6>.
68. Das UN. Essential fatty acids and their metabolites in the pathobiology of inflammation and its resolution. *Biomolecules.* 2021;11(12):1873. <https://doi.org/10.3390/biom11121873>.
69. Calder PC. Polyunsaturated fatty acids and inflammatory processes: new twists in an old tale. *Biochimie.* 2009;91(6):791–5. <https://doi.org/10.1016/j.biochi.2009.01.008>.

70. Dennis EA, Norris PC. Eicosanoid storm in infection and inflammation. *Nat Rev Immunol*. 2015;15(8):511–23. <https://doi.org/10.1038/nri3859>.
71. Hanna VS, Hafez EA. Synopsis of arachidonic acid metabolism: A review. *J Adv Res*. 2018;11:23–32. <https://doi.org/10.1016/j.jare.2018.03.005>.
72. Shahidi F, Ambigaipalan P. Omega-3 polyunsaturated fatty acids and their health benefits. *Annual Rev food Sci Technol*. 2018;9:345–81. <https://doi.org/10.1146/annurev-food-111317-095850>.
73. Calder PC. Omega-3 fatty acids and inflammatory processes: from molecules to man. *Biochem Soc Trans*. 2017;45(5):1105–15. <http://dx.doi.org/10.1042/BST20160474>.
74. Linker RA, Lee DH, Ryan S, van Dam AM, Conrad R, Bista P, Zeng W, Hronowsky X, Buko A, Chollate S, Ellrichmann G. Fumaric acid esters exert neuroprotective effects in neuroinflammation via activation of the Nrf2 antioxidant pathway. *Brain*. 2011;134(3):678–92. <https://doi.org/10.1093/brain/awq386>.
75. Mrowietz U, Asadullah K. Dimethylfumarate for psoriasis: more than a dietary curiosity. *Trends Mol Med*. 2005;11(1):43–. <https://doi.org/10.1016/j.molmed.2004.11.003>. 8.
76. Mills EL, Ryan DG, Prag HA, Dikovskaya D, Menon D, Zaslona Z, Jedrychowski MP, Costa AS, Higgins M, Hams E, Szpyt J. Itaconate is an anti-inflammatory metabolite that activates Nrf2 via alkylation of KEAP1. *Nature*. 2018;556(7699):113–7. <https://doi.org/10.1038/nature25986>.
77. Davidson PM, Sofos JN, Branen AL. Antimicrobials in food. Volume 28. CRC; 2005 Apr. <https://doi.org/10.1201/9781420028737>.
78. Russell NJ, Gould GW, editors. *Food Preservatives*. 2nd ed. Boston: Springer; 2003. <https://doi.org/10.1007/978-0-387-30042-9>.
79. Pacheco MM, Moreno HT, Torres RS, Ramírez LA, Romero JC. Natural Products with Antimicrobial Properties. In *Natural Products in Drug Discovery 2026* (pp. 55–84). <https://doi.org/10.1201/9781998511297-4>
80. Knothe G, Dunn RO. Dependence of oil stability index of fatty compounds on their structure and concentration and presence of metals. *J Am Oil Chem Soc*. 2003;80(10):1021–6. <https://doi.org/10.1007/s11746-003-0814-x>.
81. Gunstone FD. Fatty acid and lipid chemistry. Springer; 2012 Dec. p. 6. <https://doi.org/10.1007/978-1-4615-4131-8>.
82. Ferdinandusse S, Denis S, Faust PL, Wanders RJ. Bile acids: the role of peroxisomes. *J Lipid Res*. 2009;50(11):2139–47. <https://doi.org/10.1194/jlr.R900009-JLR200>.
83. Lang T, Halemani ND, Rammner B. Interplay between lipids and the proteinaceous membrane fusion machinery. *Prog Lipid Res*. 2008;47(6):461–9. <https://doi.org/10.1016/j.plipres.2008.08.002>.
84. Fitton A, Goa KL. Azelaic acid: a review of its pharmacological properties and therapeutic efficacy in acne and hyperpigmentary skin disorders. *Drugs*. 1991;41(5):780–98. <https://doi.org/10.2165/00003495-199141050-00007>.
85. Gunstone F, editor. *Vegetable oils in food technology: composition, properties and uses*. Volume 1. Wiley; 2011 Mar. <https://doi.org/10.1002/9781444339925.ch1>.
86. Sieber MA, Hegel JK. Azelaic acid: properties and mode of action. *Skin Pharmacol Physiol*. 2013;27(Suppl 1):9–17. <https://doi.org/10.1159/000354888>.
87. Kornhauser A, Coelho SG, Hearing VJ. Applications of hydroxy acids: classification, mechanisms, and photoactivity. *Clinical, cosmetic and investigational dermatology*. 2010 Nov 24:135–42. <https://doi.org/10.2147/CCID.S9042>
88. Field CJ, Blewett HH, Proctor S, Vine D. Human health benefits of vaccenic acid. *Applied Physiology. Nutr Metabolism*. 2009;34(5):979–91. <https://doi.org/10.1139/H09-079>.
89. Jacome-Sosa MM, Borthwick F, Mangat R, Uwiera R, Reaney MJ, Shen J, Quiroga AD, Jacobs RL, Lehner R, Proctor SD. Diets enriched in trans-11 vaccenic acid alleviate ectopic lipid accumulation in a rat model of NAFLD and metabolic syndrome. *J Nutr Biochem*. 2014;25(7):692–701. <https://doi.org/10.1016/j.jnutbio.2014.02.011>.
90. Turpeinen AM, Mutanen M, Aro A, Salminen I, Basu S, Palmquist DL, Griinari JM. Bioconversion of vaccenic acid to conjugated linoleic acid in humans. *Am J Clin Nutr*. 2002;76(3):504–10. <https://doi.org/10.1093/ajcn/76.3.504>.
91. Sales-Campos H, Reis de Souza P, Crema Peghini B, Santana da Silva J, Ribeiro Cardoso C. An overview of the modulatory effects of oleic acid in health and disease. *Mini Rev Med Chem*. 2013;13(2):201–10. <https://doi.org/10.2174/138955713804805193>.
92. López S, Bermúdez B, Pacheco YM, Villar J, Abia R, Muriana FJ. Distinctive postprandial modulation of β cell function and insulin sensitivity by dietary fats: monounsaturated compared with saturated fatty acids. *Am J Clin Nutr*. 2008;88(3):638–44. <https://doi.org/10.1093/ajcn/88.3.638>.
93. Singh S, Semwal BC, Singh B, Singh AP, Panda SP, Vanillin. A Review on the Therapeutic Potential as an Anti-inflammatory Agent. *Recent Adv Inflamm Allergy Drug Discovery*. 2025. <https://doi.org/10.2174/0127722708368753250713180110>.

94. Schwingshackl L, Hoffmann G. Monounsaturated fatty acids, olive oil and health status: a systematic review and meta-analysis of cohort studies. *Lipids Health Dis.* 2014;13(1):154. <https://doi.org/10.1186/1476-511X-13-154>.
95. Zhao Z, Yang Q, Sun Y, Ruan X. Unveiling the antioxidant and anti-inflammatory potential of syringic acid: mechanistic insights and pathway interactions. *Front Pharmacol.* 2025;16:1615294. <https://doi.org/10.3389/fphar.2025.1615294>.
96. Wei R, Zimmermann W. Microbial enzymes for the recycling of recalcitrant petroleum-based plastics: how far are we? *Microb Biotechnol.* 2017;10(6):1308–22. <https://doi.org/10.1111/1751-7915.12710>.
97. Danso D, Chow J, Streit WR. Plastics: environmental and biotechnological perspectives on microbial degradation. *Appl Environ Microbiol.* 2019;85(19):e01095–19. <https://doi.org/10.1128/AEM.01095-19>.
98. Webb HK, Arnott J, Crawford RJ, Ivanova EP. Plastic degradation and its environmental implications with special reference to poly (ethylene terephthalate). *Polymers.* 2012;5(1):1–8. <https://doi.org/10.3390/polym5010001>.
99. Wanders RJ, Waterham HR. Biochemistry of mammalian peroxisomes revisited. *Annu Rev Biochem.* 2006;75(1):295–332. <https://doi.org/10.1146/annurev.biochem.74.082803.133329>.
100. Rinaldo P, Matern D, Bennett MJ. Fatty acid oxidation disorders. *Annu Rev Physiol.* 2002;64(1):477–502. <https://doi.org/10.1146/annurev.physiol.64.082201.154705>.
101. Tournier V, Topham CM, Gilles A, David B, Folgoas C, Moya-Leclair E, Kamionka E, Desrousseaux ML, Texier H, Gavalda S, Cot M. An engineered PET depolymerase to break down and recycle plastic bottles. *Nature.* 2020;580(7802):216–9. <https://doi.org/10.1038/s41586-020-2149-4>.
102. Wishart DS, Feunang YD, Marcu A, Liang K, Vazquez-Fresno R, Sajed T, Johnson D, Li C, Karu N, Sayeeda Z, Lo E. HMDB 4.0: the human metabolome database for 2018. *Nucleic Acids Res.* 2018;46(D1):D608–17. <https://doi.org/10.1093/nar/gkx1089>.
103. Kim HK, Choi YH, Verpoorte R. NMR-based metabolomic analysis of plants. *Nat Protoc.* 2010;5(3):536–49. <https://doi.org/10.1038/nprot.2009.237>.
104. Espíndola KM, Ferreira RG, Narvaez LE, Silva Rosario AC, Da Silva AH, Silva AG, Vieira AP, Monteiro MC. Chemical and pharmacological aspects of caffeic acid and its activity in hepatocarcinoma. *Front Oncol.* 2019;9:541. <https://doi.org/10.3389/fonc.2019.00541>.
105. Magnani C, Isaac VL, Correa MA, Salgado HR. Caffeic acid: a review of its potential use in medications and cosmetics. *Anal Methods.* 2014;6(10):3203–10. <https://doi.org/10.1039/c3ay41807c>.
106. Naveed M, Hejazi V, Abbas M, Kamboh AA, Khan GJ, Shumzaid M, Ahmad F, Babazadeh D, FangFang X, Modarresi-Ghazani F, WenHua L. Chlorogenic acid (CGA): A pharmacological review and call for further research. *Biomed Pharmacother.* 2018;97:67–74. <https://doi.org/10.1016/j.biopha.2017.10.064>.
107. Fuchs G, Boll M, Heider J. Microbial degradation of aromatic compounds—from one strategy to four. *Nat Rev Microbiol.* 2011;9(11):803–16. <https://doi.org/10.1038/nrmicro2652>.
108. Shrivastava R, Phale PS. Biodegradation of mono-aromatic compounds by bacteria. In *Microorganisms Environ Manage.* 2012;451–76. https://doi.org/10.1007/978-94-007-2229-3_21.
109. Cartwright CD, Thompson IP, Burns RG. Degradation and impact of phthalate plasticizers on soil microbial communities. *Environ Toxicol Chem.* 2000;19(5):1253–61. <https://doi.org/10.1002/etc.5620190506>.
110. Harwood CS, Parales RE. The β -ketoadipate pathway and the biology of self-identity. *Annu Rev Microbiol.* 1996;50(1):553–90. <https://doi.org/10.1146/annurev.micro.50.1.553>.
111. Yoshida S, Hiraga K, Takehana T, Taniguchi I, Yamaji H, Maeda Y, Toyohara K, Miyamoto K, Kimura Y, Oda K. A bacterium that degrades and assimilates poly (ethylene terephthalate). *Science.* 2016;351(6278):1196–9. <https://doi.org/10.1126/science.aad6359>.
112. Roy RN, Laskar S, Sen SK. Dibutyl phthalate, the bioactive compound produced by *Streptomyces albidoflavus* 321.2. *Microbiol Res.* 2006;161(2):121–6. <https://doi.org/10.1016/j.micres.2005.06.007>.
113. Staples CA, Peterson DR, Parkerton TF, Adams WJ. The environmental fate of phthalate esters: a literature review. *Chemosphere.* 1997;35(4):667–749. [https://doi.org/10.1016/S0045-6535\(97\)00195-1](https://doi.org/10.1016/S0045-6535(97)00195-1).
114. Vlot AC, Dempsey DM, Klessig DF. Salicylic acid, a multifaceted hormone to combat disease. *Annu Rev Phytopathol.* 2009;47(1):177–206. <https://doi.org/10.1146/annurev.phyto.050908.135202>.
115. Hayat Q, Hayat S, Irfan M, Ahmad A. Effect of exogenous salicylic acid under changing environment: a review. *Environ Exp Bot.* 2010;68(1):14–25. <https://doi.org/10.1016/j.envexpbot.2009.08.005>.
116. Raskin I. Role of salicylic acid in plants. *Annu Rev Plant Biol.* 1992;43(1):439–. <https://doi.org/10.1146/annurev.pp.43.060192.002255>.
117. Fernie AR, Carrari F, Sweetlove LJ. Respiratory metabolism: glycolysis, the TCA cycle and mitochondrial electron transport. *Curr Opin Plant Biol.* 2004;7(3):254–61. <https://doi.org/10.1016/j.pbi.2004.03.007>.

118. Igamberdiev AU, Eprintsev AT. Organic acids: the pools of fixed carbon involved in redox regulation and energy balance in higher plants. *Front Plant Sci.* 2016;7:1042. <https://doi.org/10.3389/fpls.2016.01042>.
119. Sweetlove LJ, Beard KF, Nunes-Nesi A, Fernie AR, Ratcliffe RG. Not just a circle: flux modes in the plant TCA cycle. *Trends Plant Sci.* 2010;15(8):462–70. <https://doi.org/10.1016/j.tplants.2010.05.006>.
120. O'Leary B, Park J, Plaxton WC. The remarkable diversity of plant PEPC (phosphoenolpyruvate carboxylase): recent insights into the physiological functions and post-translational controls of non-photosynthetic PEPCs. *Biochem J.* 2011;436(1):15–34. <https://doi.org/10.1042/BJ20110078>.
121. Samuels L, Kunst L, Jetter R. Sealing plant surfaces: cuticular wax formation by epidermal cells. *Annu Rev Plant Biol.* 2008;59:683–707. <https://doi.org/10.1146/annurev.arplant.59.103006.093219>.
122. Kunst L, Samuels L. Plant cuticles shine: advances in wax biosynthesis and export. *Curr Opin Plant Biol.* 2009;12(6):721–7. <https://doi.org/10.1016/j.pbi.2009.09.009>.
123. Yeats TH, Rose JK. The formation and function of plant cuticles. *Plant Physiol.* 2013;163(1):5–20. <https://doi.org/10.1104/pp.113.222737>.
124. Pfeuffer M, Jaudszus A. Pentadecanoic and heptadecanoic acids: multifaceted odd-chain fatty acids. *Adv Nutr.* 2016;7(4):730–4. <https://doi.org/10.3945/an.115.011387>.
125. Forouhi NG, Koulman A, Sharp SJ, Imamura F, Kröger J, Schulze MB, Crowe FL, Huerta JM, Guevara M, Beulens JW, van Woudenberg GJ. Differences in the prospective association between individual plasma phospholipid saturated fatty acids and incident type 2 diabetes: the EPIC-InterAct case-cohort study. *lancet Diabetes Endocrinol.* 2014;2(10):810–8. [https://doi.org/10.1016/S2213-8587\(14\)70146-9](https://doi.org/10.1016/S2213-8587(14)70146-9).
126. Wallace H, Knutsen HK, Alexander J, Barregård L, Bignami M, Brüschweiler B, Ceccatelli S, Dinovi M, Edler L, Grasl-Kraupp B, Hogstrand C. Erucic acid in feed and food. *EFSA J.* 2016;14(11):1–73. <https://doi.org/10.2903/j.efsa.2016.4593>.
127. Ramadan MF, editor. *Fruit oils: Chemistry and functionality.* Switzerland: Springer; 2019 May. p. 8. <https://doi.org/10.1007/978-3-030-12473-1>.
128. Kahkeshani N, Farzaei F, Fotouhi M, Alavi SS, Bahramsoltani R, Naseri R, Momtaz S, Abbasabadi Z, Rahimi R, Farzaei MH, Bishayee A. Pharmacological effects of gallic acid in health and diseases: A mechanistic review. *Iran J basic Med Sci.* 2019;22(3):225. <https://doi.org/10.22038/ijbms.2019.32806.7897>.
129. Badhani B, Sharma N, Kakkar R. Gallic acid: A versatile antioxidant with promising therapeutic and industrial applications. *RSC Adv.* 2015;5(35):27540–57. <https://doi.org/10.1039/c5ra01911g>.
130. Borges A, Ferreira C, Saavedra MJ, Simões M. Antibacterial activity and mode of action of ferulic and gallic acids against pathogenic bacteria. *Microb drug Resist.* 2013;19(4):256–65. <https://doi.org/10.1089/mdr.2012.0244>.
131. Lin HH, Chen JH, Chou FP, Wang CJ. Protocatechuic acid inhibits cancer cell metastasis involving the down-regulation of Ras/Akt/NF- κ B pathway and MMP-2 production by targeting RhoB activation. *Br J Pharmacol.* 2011;162(1):237–54. <https://doi.org/10.1111/j.1476-5381.2010.01022.x>.
132. Kakkar S, Bais S. A review on protocatechuic acid and its pharmacological potential. *Int Sch Res Notices.* 2014;2014(1):952943. <https://doi.org/10.1155/2014/952943>.
133. Heleno SA, Martins A, Queiroz MJ, Ferreira IC. Bioactivity of phenolic acids: Metabolites versus parent compounds: A review. *Food Chem.* 2015;173:501–13. <https://doi.org/10.1016/j.foodchem.2014.10.057>.
134. López-Herrador S, Corral-Sarasa J, González-García P, Morillas-Morota Y, Olivieri E, Jiménez-Sánchez L, Díaz-Casado ME. Natural hydroxybenzoic and hydroxycinnamic acids derivatives: mechanisms of action and therapeutic applications. *Antioxidants.* 2025;14(6):711. <https://doi.org/10.3390/antiox14060711>.
135. Kumar N, Goel N. Phenolic acids: Natural versatile molecules with promising therapeutic applications. *Biotechnol Rep.* 2019;24:e00370. <https://doi.org/10.1016/j.btre.2019.e00370>.
136. Ashidate K, Kawamura M, Mimura D, Tohda H, Miyazaki S, Teramoto T, Yamamoto Y, Hirata Y. Gentisic acid, an aspirin metabolite, inhibits oxidation of low-density lipoprotein and the formation of cholesterol ester hydroperoxides in human plasma. *Eur J Pharmacol.* 2005;513(3):173–9. <https://doi.org/10.1016/j.ejphar.2005.03.012>.
137. Khadem S, Marles RJ. Monocyclic phenolic acids; hydroxy- and polyhydroxybenzoic acids: occurrence and recent bioactivity studies. *Molecules.* 2010;15(11):7985–8005. <https://doi.org/10.3390/molecules15117985>.
138. Singh BN, Shankar S, Srivastava RK. Green tea catechin, epigallocatechin-3-gallate (EGCG): mechanisms, perspectives and clinical applications. *Biochem Pharmacol.* 2011;82(12):1807–21. <https://doi.org/10.1016/j.bcp.2011.07.093>.

139. Kumar S, Pandey AK. Chemistry and biological activities of flavonoids: an overview. *Sci world J.* 2013;2013(1):162750. <https://doi.org/10.1155/2013/162750>.
140. Bernatoniene J, Kopustinskiene DM. The role of catechins in cellular responses to oxidative stress. *Molecules.* 2018;23(4):965. <https://doi.org/10.3390/molecules23040965>.
141. Bernatova I. Biological activities of (–)-epicatechin and (–)-epicatechin-containing foods: Focus on cardiovascular and neuropsychological health. *Biotechnol Adv.* 2018;36(3):666–81. <https://doi.org/10.1016/j.biotechadv.2018.01.009>.
142. Valdivieso-Ugarte M, Gomez-Llorente C, Plaza-Díaz J, Gil Á. Antimicrobial, antioxidant, and immunomodulatory properties of essential oils: A systematic review. *Nutrients.* 2019;11(11):2786. <https://doi.org/10.3390/nu11112786>.
143. Bao X, Katz S, Pollard M, Ohlrogge J. Carbocyclic fatty acids in plants: Biochemical and molecular genetic characterization of cyclopropane fatty acid synthesis of *Sterculia foetida*. *Proceedings of the National Academy of Sciences.* 2002;99(10):7172-7. <https://doi.org/10.1073/pnas.092152999>
144. Grogan DW, Cronan JE Jr. Cyclopropane ring formation in membrane lipids of bacteria. *Microbiol Mol Biol Rev.* 1997;61(4):429–. <https://doi.org/10.1128/mmbr.61.4.429-441.1997>. 41.
145. Ohlrogge J, Browse J. Lipid. biosynthesis. *The plant cell.* 1995;7(7):957. <https://doi.org/10.1105/tpc.7.7.957>
146. Haslam TM, Kunst L. Extending the story of very-long-chain fatty acid elongation. *Plant Sci.* 2013;210:93–107. <https://doi.org/10.1016/j.plantsci.2013.05.008>.
147. Chen J, Henderson G, Laine RA. Lignoceric acid and hexacosanoic acid: Major components of soldier frontal gland secretions of the Formosan subterranean termite (*Coptotermes formosanus*). *J Chem Ecol.* 1999;25(4):817–24. <https://doi.org/10.1023/A:1020844817492>.
148. Tretter L, Patocs A, Chinopoulos C. Succinate, an intermediate in metabolism, signal transduction, ROS, hypoxia, and tumorigenesis. *Biochim et Biophys Acta (BBA)-Bioenergetics.* 2016;1857(8):1086–101. <https://doi.org/10.1016/j.bbabo.2016.03.012>.
149. Murphy MP, O'Neill LA. Krebs cycle reimagined: the emerging roles of succinate and itaconate as signal transducers. *Cell.* 2018;174(4):780–4. <https://doi.org/10.1016/j.cell.2018.07.030>.
150. Araujo WL, NUNES-NESI AD, Nikoloski Z, Sweetlove LJ, Fernie AR. Metabolic control and regulation of the tricarboxylic acid cycle in photosynthetic and heterotrophic plant tissues. *Plant Cell Environ.* 2012;35(1):1–21. <https://doi.org/10.1111/j.1365-3040.2011.02332.x>.

Figures

