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An in-depth review of the phytochemical profile and pharmacological potential of *Oenocarpus bataua*

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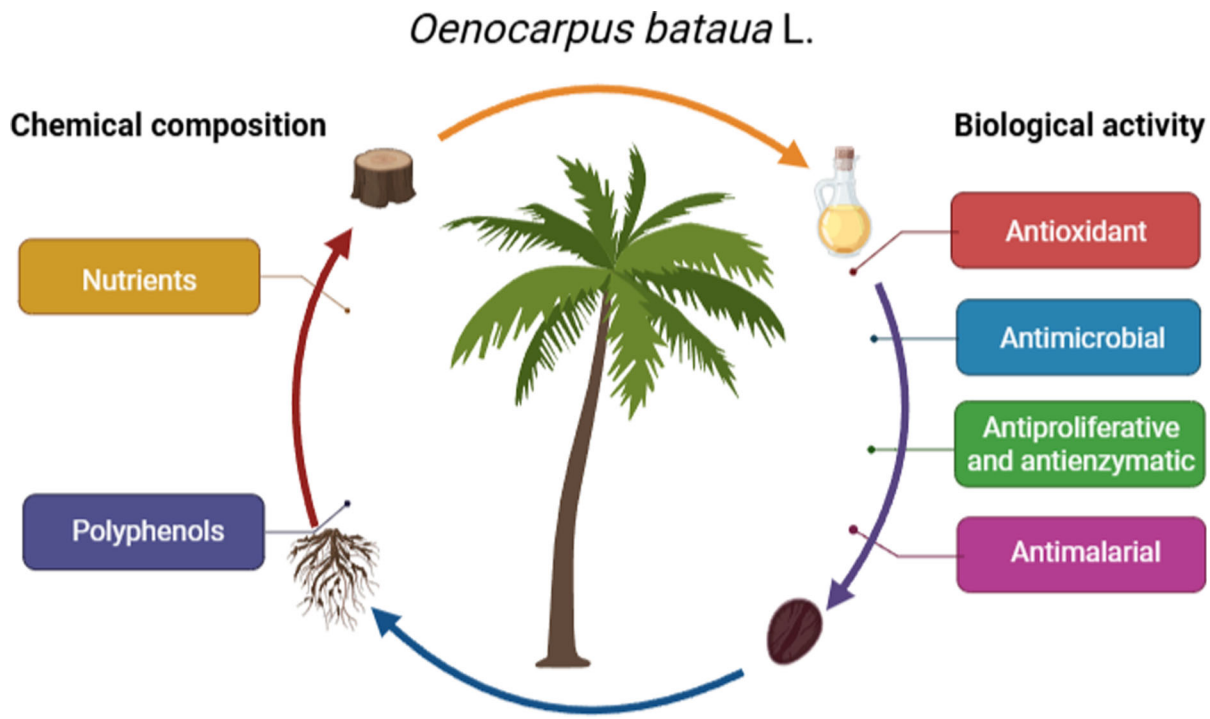
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Abstract The Amazonian palm, *Oenocarpus bataua*, is a popular palm used for food and medicinal purposes. Due to its widespread use and therapeutic potential, this species was investigated to identify its phytochemical compounds and correlate them with the associated pharmacological activities. This data was then organized and presented in this study to provide an overview of different aspects of this plant species. This review examines the current research landscape surrounding this Amazonian species through a comprehensive analysis of the existing literature. It consists of an analysis of articles published up to 2025 found in the following virtual databases: PubMed, ScienceDirect, SciELO, LILACS, and Web of Science, using the descriptors: "*Oenocarpus bataua*, chemical composition and pharmacological activity" and their combinations, refining the findings with the Boolean operators AND and OR. *O. bataua* contains a wide diversity of bioactive components, being rich in nutrients and polyphenols. Its extracts have also been shown to exhibit antioxidant, antimicrobial, antiproliferative, antienzymatic, and antimalarial activity. Therefore, understanding these aspects may provide new perspectives for the development of dietary and pharmacological interventions aimed at preventing or treating specific disease pathologies and improving quality of life. Despite the nutritional, functional, and pharmacological value previously described for this plant species, it still remains vastly unexplored, which presents a significant opportunity for further research aimed at product development. There is a need to delve deeper into the chemical profile, biological activity and safety of this interesting Amazonian palm tree.

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Graphical abstract



Keywords Arecaceae · *Oenocarpus bataua* · Phytochemistry · Biological activity · Phenolic compounds · Antioxidant activity

Introduction

The Amazon biome hosts a vast array of plant species with significant economic potential for biotechnological and industrial applications, owing to their nutritional and pharmacological properties that address global consumption and production demands (Ibiapina et al. 2022). Consequently, native Amazonian palms have become focal points for research and product development (Gomes et al. 2022). In recent years, new strategies for delivering bioactive compounds have emerged, increasingly prioritizing the use of natural ingredients (Ferreira et al. 2023, 2024a, 2024b, 2024c; Mosquera Narvaez et al. 2022; Narvaez et al. 2023; Sanches et al. 2023, 2024).

Within this context, the Arecaceae family (Palmae) constitutes a monophyletic group of significant botanical relevance, comprising approximately 2600 species across 181 genera, with centers of diversity primarily concentrated in tropical and subtropical ecosystems (Tomlinson 2006; Eiserhardt et al. 2011; Baker and Dransfield 2016; Emílio et al. 2019). Given their substantial population density and species richness, palms serve as keystone elements in maintaining and structuring community dynamics within tropical forests (Roncal et al. 2005; Avalos et al. 2022). From economic and ethnobotanical perspectives, the family offers a broad spectrum of utilities, ranging from ornamental and dietary resources (De Souza et al. 2020) to phytochemical and traditional therapeutic applications (Ayokun-nun Ajao et al. 2021). Furthermore, anthropogenic management and commercial exploitation have directly shaped the biogeographical patterns and natural distribution of this taxon (Eiserhardt et al. 2011).

Biological derivatives from the Arecaceae family serve as strategic inputs that sustain local economies and integrate transnational trade chains, functioning as vital resources for the livelihoods of traditional communities (Baker et al. 2009; Baker and Couvreur

2013). From an ecological perspective, their fruits provide an essential trophic base for both wildlife and human populations, acting as pivotal components of fundamental ecosystem services—most notably in pollination dynamics and the preservation of gene flow through propagule dispersal (Bellot et al. 2024; Fadini et al. 2009).

In this context, the genus Oenocarpus (Arecaceae) exhibits an extensive phytogeographical distribution, spanning from the seasonally flooded forest formations (várzeas) of southern Costa Rica to the Maracaibo Basin in Venezuela, with a prominent presence in the western and central Amazon Basin (Romero-Orejón et al., 2023). The genus encompasses ecologically and economically significant taxa, most notably *O. bacaba*, *O. distichus*, *O. mapora*, and *O. bataua*. Morphologically, the infrutescences yield fruits with phenotypic variations ranging from elliptical to globose. Upon reaching physiological maturity, the epicarp develops an atropurpureus (dark purple) coloration—a diagnostic trait used to determine the optimal harvest stage and fruit ripeness across the genus (Romero-Orejón et al. 2023).

Oenocarpus bataua Mart., known by various vernacular names such as "patauá" and "ungurahui," is native to the Amazon Basin and surrounding areas (Fig. 1). It is a key resource for local communities, who use it for food, traditional medicine, and the production of nutritious drinks (Jaramillo-Vivanco et al. 2022; Méndez-Durazno et al. 2023). Although the species is abundant and an important source of oil (Cardona Jaramillo et al. 2019), its chemical profile and industrial applications in the food and cosmetic sectors are still underexplored (Leba et al. 2016). Characterizing its properties is crucial for developing high-value products (Sánchez-Capa et al. 2023) and promoting the sustainable use of Amazonian biodiversity (Burlando and Cornara 2017).

To unlock the therapeutic potential of this species, a rigorous evaluation of its chemical composition is required (Cardona Jaramillo et al. 2019). Although its biological properties remain under-researched (Leba et al. 2016), recent studies highlight the fruit as a promising Amazonian resource, exhibiting antioxidant activity that surpasses even that of açaí—a fruit widely recognized for its high antioxidant capacity (Rezaire et al. 2014). Moreover, evidence suggests that *O. bataua* is a significant source of bioactive compounds (Méndez-Durazno et al. 2023), and its consumption may offer an alternative strategy for preventing neurodegenerative diseases and related non-communicable chronic conditions (Vargas-Arana

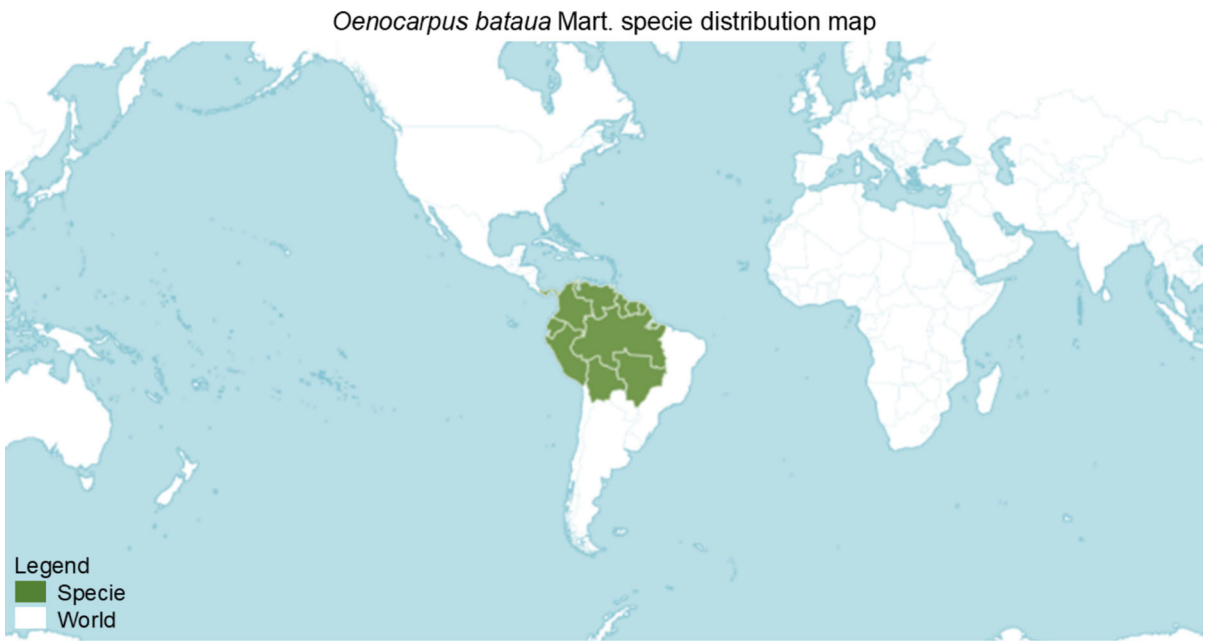


Fig. 1 Distribution of *Oenocarpus bataua* specie worldwide. Adapted from Plants of the World Online, by Royal Botanic Gardens, Kew, 2026 (powo.science.kew.org). https://BioRender.com

et al. 2022). Consequently, investigating "patauá" and its bioactive constituents is essential to facilitate its application in future biomedical research (Lima et al. 2025).

This review aims to synthesize existing scientific literature regarding the physicochemical composition and bioactive compounds of *O. bataua*, highlighting its potential for broader exploration. To the best of our knowledge, this represents the most comprehensive overview of the species to date, providing a robust foundation for future mechanistic studies and scientific advancement. By emphasizing the value of this Amazonian species, this work fosters the development of biotechnologies aligned with green innovation and the sustainable use of natural resources. Consequently, it supports the United Nations Sustainable Development Goals (SDGs), specifically SDG 3 (Good Health and Well-being), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 12 (Responsible Consumption and Production). By integrating science, innovation, and sustainability, this research underscores the strategic role of Amazonian biodiversity in developing effective and socially responsible pharmaceutical solutions. Furthermore, it provides a scientific basis for public policies on integrative health and sustainable territorial development, demonstrating *O. bataua* as a versatile source of antioxidant, antimicrobial, antiproliferative, antienzymatic, and antimalarial agents. These findings are poised to catalyze the development of high-value natural products, such as cosmetics and medicines, while promoting local production with a reduced environmental footprint.

Methodology

An extensive literature review was conducted to investigate existing literature on the plant species *O. bataua*, using the following databases: National Library of Medicine (PubMed), ScienceDirect, Scientific Electronic Library Online (SciELO), Latin American and Caribbean Literature in Health Sciences (LILACS), and Web of Science. The descriptors were placed separately in quotation marks, specifying the search combinations used: "*Oenocarpus bataua*" AND "Chemical composition"; "*Oenocarpus bataua*" AND "Pharmacological activity". The keyword selection aimed to refine and enrich our strategy, ensuring more objective and relevant results. After the initial search, the results were exported to a reference manager to identify and remove duplicate entries. Each study was counted only once to ensure the integrity of the quantitative analysis.

Inclusion criteria

The inclusion criteria were limited to all original articles, experimental studies, and clinical studies which focused on the Chemical composition and Pharmacological activity of *O. bataua*.

Exclusion criteria

Inventions, reviews, newspaper articles, editorials and inaccessible articles were excluded.

Geographic distribution the species *O. bataua*

Following the implementation of the methodology, a rigorous document review was conducted to select the most pertinent studies for this research. These articles served to characterize the chemical composition, bioactive constituents, and biological activities of the species as reported in the scientific literature. The findings are structured into two subsections: the first summarizes the chemical profile and identifies potential bioactive components, while the second details the biological activities evidenced in *O. bataua* samples to elucidate the species' therapeutic potential. Data analysis revealed that the majority of studies were conducted in the Peruvian Amazon, with the fruit and pulp being the most frequently investigated parts (Table 1). Notably, many studies failed to provide precise geographic coordinates, such as latitude and longitude, for the collection sites (Tables 1 and 2).

Chemical aspects

Studies indicate that the fruit pulp and its derived oil possess significant mineral concentrations; however, specific data regarding the seeds, leaves, roots, and epicarp (peel) remain limited. These structures are expected to exhibit mineral profiles characteristic of other Arecaceae species—notably potassium, calcium, and phosphorus—though potentially in lower concentrations. Despite the relative scarcity of comprehensive nutritional reports, *O. bataua* is recognized

Table 1 Geographic distribution of collection sites according to the analyzed vegetative part (fruit, fruit and root, fruit and pulp, fruit/pulp) of the species *O. bataua*

Organ	Location	District/ Department	Province/ State	Region	Latitude	Longitude	References
Fruit	Montsinéry–Tonnegrande	NR	NR	Guiana Francesa	NR	NR	(Rezaire et al. 2014)
Fruit and root	Iquitos	NR	NR	NR	NR	NR	(Roumy et al. 2015)
Fruit and pulp	Bellavista—Amazônia peruana	Santa Rosa de Yavarí	Mariscal Ramón Castilla	Loreto	03°56′13.34″S	70°13′28.66″W	(Vargas-Arana et al. 2022)
	Hacienda Concepción—Amazônia peruana	Tambopata	Tambopata	Madre de Dios	12°36′34.27″S	69°04′49.12″W	
	Jenaro Herrera—Amazônia peruana	Jenaro Herrera	Requena	Loreto	04°55′11.63″S	73°36′48.57″W	
	Contamana—Amazônia peruana	Contamana	Ucayali	Loreto	07°18′38.93″S	75°00′10.76″W	
	Allpahuayo Mishana—Amazônia peruana	San Juan Bautista	Maynas	Loreto	03°57′48.52’’S	73°25′09.40’’W	
	San Lorenzo—Amazônia peruana	Barranca	Datem del Marañón	Loreto	04°43′55.49″S	76 31′02.79″W	
	Atalaya—Amazônia peruana	Atalaya	Atalaya	Ucayali	10°42′26.79″S	73°47′40.29″W	
	Palestina—Amazônia peruana	Nueva Cajamarca	Rioja	San Martín	05°55′0.00″S	77°21′15.19″W	
	Tunaants—Amazônia peruana	Nieva	Condorcanqui	Amazonas	04°36′55.36″S	77°52′14.99″W	
Fruit/ pulp	Mercados da cidade de Manaus	NR	Manaus	Amazonas	3°03′22″S	60°00′22″W	(Lima et al. 2025)

Not reported (NR)

for its substantial nutrient content, particularly high concentrations of calcium (Ca), magnesium (Mg), and sodium (Na). Furthermore, the mineral composition varies significantly across the different botanical structures of the species (Table 3).

The ethanolic bark extract of this species exhibited a remarkably high Total Phenolic Content (TPC) of 1,009,380 µg/mL (Table 4). Similarly, the bark displayed the highest total anthocyanin levels. Regarding total yellow flavonoids, no significant differences were observed among the ethanolic extracts of the pulp, epicarp (peel), and seeds (Table 4). Notably, as data on the phenolic, anthocyanin, and flavonoid profiles of this fruit remain scarce, this study likely represents the first report on *O. bataua* bark and seeds from the Ecuadorian Amazon. Furthermore, acetonic/aqueous extracts of leaves and roots yielded the highest TPC, followed by their methanolic/aqueous counterparts, with leaf extracts consistently showing higher polyphenol concentrations than those from roots (Table 4). While these specific vegetative organs were sourced from French Guiana (Tables 1 and 2), the TPC analysis of the fruit revealed that methanolic/aqueous extraction was more effective than aqueous or acetonic methods.

Several phenolic compounds were identified in the fruit extract of this species (Fig. 2), with chlorogenic acid as the predominant constituent (2324.7 ng/g DW), followed by vanillic, syringic, *p*-coumaric, ferulic, and caffeic acids. Among the flavonoids, epicatechin (8628.5 ng/g DW) and hesperidin (5222 ng/g DW) occurred in the highest

Table 2 Geographic distribution of collection sites according to the analyzed vegetative part (peel, pulp and seed, leaf and root, oil and peel, pulp and seed) of the species *O. bataua*

Organ	Location	District/ Department	Province/ State	Region	Latitude	Longitude	References
Peel, pulp and seed	Reserva Florestal Adolpho Ducke	NR	Manaus	NR	NR	NR	(Hidalgo et al. 2016)
Leaf and root	Macouria	NR	NR	Guiana Francesa	NR	NR	(Leba et al. 2016)
Oil	Estação experimental "El Trueno" (Instituto Amazónico de Investigaciones Científicas Sinchi), localizada entre San José del Guaviare e El Retorno—Amazônia colombiana	NR	NR	NR	2°24′N	72°43′W	(Cardona Jaramillo et al. 2019)
Peel, pulp and seed	Tena—Amazônia equatoriana		Napo		1°00′05.5″S	77°48′44.7″W	(Méndez-Durazno et al. 2023)

Not reported (NR)

Table 3 Chemical composition according to the vegetative part of the species *O. bataua*

Organ	Chemical Composition				References
	Macronutrients				
	Proteins	Lipids	Carbohydrates	Fiber	
Fruit/Pulp	4.9 ± 0.05	14.4 ± 0.02	46.1	29.7 ± 0.14	(Darnet et al. 2011)
	17.58 ± 0.12 ^{V}	25.98 ± 0.97^{IV}	27.50^{VIII}	22.00 ± 0.47^{I}	(Vargas-Arana et al. 2022)

	Micronutrients							
	Ca	K	Mg	Na	P	Cl	S	
Fruit/ Pulp	30^{a}	138^{a}	12^{a}	6^{a}	1^{a}	14^{a}	17^{a}	(Leterme et al. 2006)
	88.14 ± 2.40^{IV}	8.31 ± 0.22^{IV}	65.29 ± 2.11^{IV}	17.39 ± 0.36^{IV}	NR	NR	NR	(Vargas-Arana et al. 2022)
Oil	0.13 ± 0.01^{b}	NR	0.71 ± 0.07^{b}	NR	0.68 ± 0.03^{b}	NR	NR	(Pereira et al. 2019)

	Zn	Cu	Fe	Mn	B	Se	Co	Ni	Cr	
Fruit/ Pulp	0.26^{a}	0.15^{a}	1.40^{a}	0.32^{a}	NR	ND	ND	ND	ND	(Leterme et al. 2006)
	1.28 ± 0.07^{III}	1.06 ± 0.02^{I}	1.18 ± 0.04^{IV}	10.60 ± 0.41^{VII}	NR	NR	NR	NR	NR	(Vargas-Arana et al. 2022)
Oil	NR	NR	0.90 ± 0.01^{b}	NR	NR	NR	NR	NR	NR	(Pereira et al. 2019)

Values of macronutrients are expressed in g.100 g^{-1} DW on a Dry Weight (DW) basis. Values expressed as mean ± SD (n = 3). ^{a}Unit: mg. 100 g^{-1} DW; ^{b}Unit: mg. kg^{-1} DW. Bellavista (I); Hacienda Concepción (II); Jenaro Herrera (III); Contamana (IV); Allpahuayo Mishana (V); San Lorenzo (VI); Atalaya (VII); Palestine (VIII); Tunaants (IX); Not reported (NR); Undetected (ND)

Table 4 Total phenolic content, anthocyanin content, and yellow flavonoids according to the vegetative part of the species *O. batatua*

Organ	Extract	TPC	TAC	TYFC	References
Leaves	Aqueous	10.1 ± 0.8	NR	NR	(Leba et al. 2016)
	Acetone/aqueous	51.1 ± 1.7	NR	NR	
	Methanolic/aqueous	24.9 ± 1.6	NR	NR	
Fruit/pulp	Acetone/aqueous	306,600 ± 7.4	NR	NR	(Rezaire et al. 2014)
	Aqueous	107.6 ± 6.2	NR	NR	(Leba et al. 2014)
	Acetone/aqueous	183.9 ± 7.2			
	Methanolic/aqueous	306.5 ± 26			
	Methanolic	72.200 ± 0.004	NR	NR	(Hidalgo et al. 2016)
	Methanolic	672.3 ± 46.9	NR	NR	(Tauchen et al. 2016)
	–	2037.70 ± 24.95 [V]	NR	NR	(Vargas-Arana et al. 2022)
	Methanolic	622,970 ± 4.84	14,820 ± 0.20	55,340 ± 0.29	(Méndez-Durazno et al. 2023)
	Methanolic	131,000 ± 9	NR	37,000 ± 3	(Lima et al. 2025)
Oil	–	–	–	–	–
Seeds	Methanolic	245.000 ± 0.005	NR	NR	(Hidalgo et al. 2016)
	Hydroethanolic	456,250 ± 1.53	NR	NR	(Navarro-Valdez et al. 2020)
	Ethanolic	758,250 ± 3.22	14,710 ± 0.02	47,150 ± 0.06	(Méndez-Durazno et al. 2023)
Peel	Ethanolic	1,009,380 ± 1.80	46,480 ± 0.31	57,170 ± 0.42	(Méndez-Durazno et al. 2023)
Root	Aqueous	9.6 ± 0.4	NR	NR	(Leba et al. 2016)
	Acetone/aqueous	33.2 ± 2.4	NR	NR	
	Methanolic/aqueous	29.2 ± 2.1	NR	NR	

Total Phenolic Content (TPC); Total Anthocyanin Content (TAC); Total Yellow Flavonoid Content (TYFC). All values are expressed as μg gallic acid equivalent per mL of extract (μg GAE/mL). Bellavista (I); Hacienda Concepción (II); Jenaro Herrera (III); Contamana (IV); Allpahuayo Mishana (V); San Lorenzo (VI); Atalaya (VII); Palestina (VIII); Tunaants (IX); Not reported (NR)

concentrations (Fig. 3). Other bioactive compounds also showed significant presence, notably isoquercitrin (2128.0 ng/g DW), cis-resveratrol (1682 ng/g DW), and isorhamnetin (1206 ng/g DW) (Fig. 4) (Tauchen et al. 2016; Lima et al. 2025).

High-performance liquid chromatography (HPLC) analysis of "patauá" fruit extract following phloroglucinolysis revealed the presence of catechin, epicatechin, and their derivatives, confirming that the fruit contains procyanidins. These compounds constitute the primary phenolics in the acetone/aqueous extract, representing 90% of the total phenolic content determined via HPLC. Notably, procyanidins were only quantifiable post-phloroglucinolysis, as flavanol monomers and dimers were detected only in trace amounts in the initial HPLC profile. The procyanidin content was approximately 18 ± 0.3 mg/g of dry pulp (12.6 ± 0.2 mg/g fresh weight). Furthermore, "patauá" is characterized by high levels of tannins, stilbenes, phenolic acids, hydroxycinnamic acids, and anthocyanins, as previously quantified (Méndez-Durazno et al. 2023; Rezaire et al. 2014; Tauchen et al. 2016; Vargas-Arana et al. 2022). Ultra-Performance Liquid Chromatography (UPLC) analysis corroborated that procyanidins are measured as the sum of all constituent units released after phloroglucinolysis, with stilbenes emerging as the predominant group of simple phenolic compounds in the fruit.

Stilbenes are predominantly found as dihexosides, collectively representing 2.6 mg of trans-piceid equivalents per gram of dry pulp. Tetrahydroxystilbene dihexoside is the primary stilbene identified (accounting for 80% of stilbene dihexosides), while trihydroxystilbene and trihydroxymethoxystilbene dihexosides occur in significantly lower concentrations. Tetrahydroxystilbene aglycone was also detected. Caffeoylquinic acids are notably abundant (1.9 mg/g DW), with 5-caffeoylquinic acid (chlorogenic acid) being the predominant form. Two syringic acid hexosides were found in equal proportions

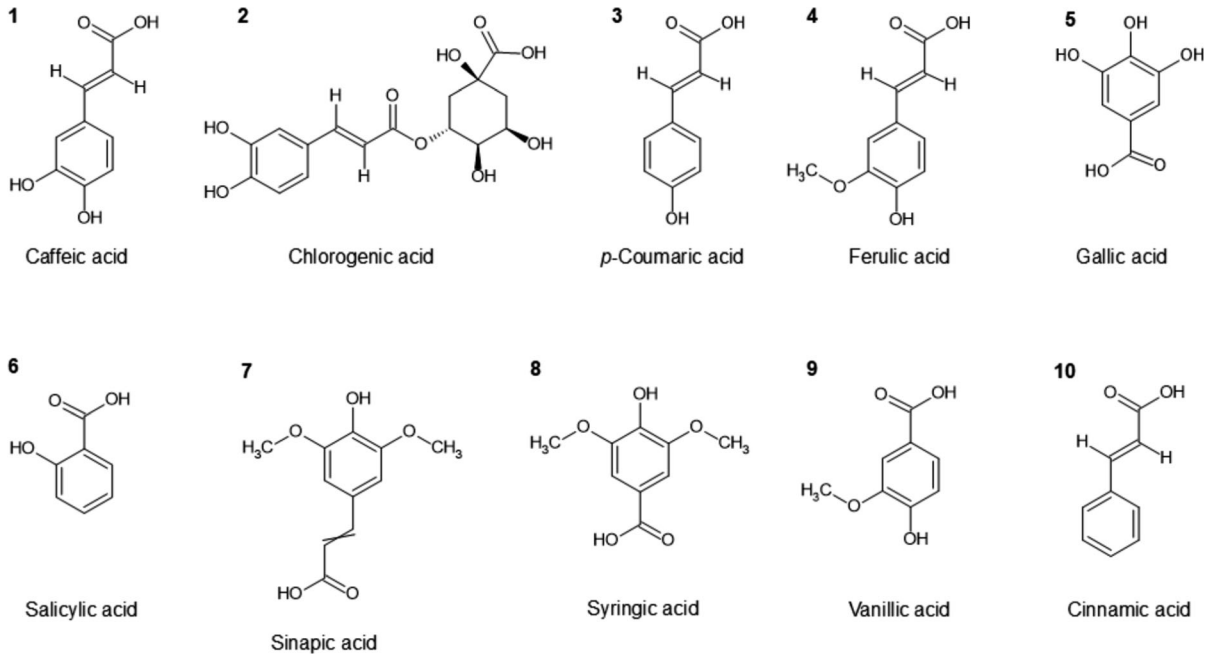


Fig. 2 Chemical structures of phenolic acids identified in the fruit extract of *O. bataua.* ACD/ChemSketch

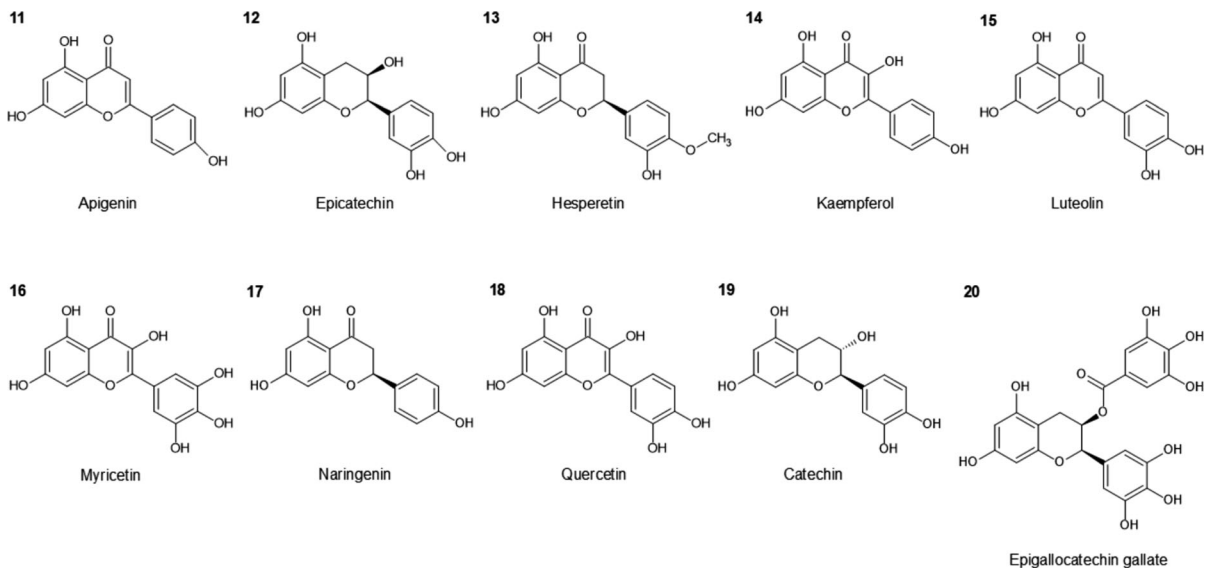


Fig. 3 Chemical structures of flavonoids identified in the fruit extract of *O. bataua.* ACD/ChemSketch

(approximately 30 µg of syringic acid equivalents/g DW). Spectrometric analysis revealed that "patauá" pulp contains 680.4 ± 26.6 mg of cyanidin-3-*O*-glucoside equivalents per kilogram of fresh weight (Rezaire et al. 2014). Additionally, trans-resveratrol, ascorbic acid, and tocopherols were identified across various vegetative extracts. The trans-resveratrol content was quantified via HPLC in the ethanolic extracts of the pulp, epicarp, and seeds (recovery rates from 90.70% to 98.10%), with its presence confirmed by UPLC-QTOF-MS at m/z 227. While α-tocopherol and other tocopherols were detected in the acetone/aqueous fruit extract, ascorbic acid levels remained

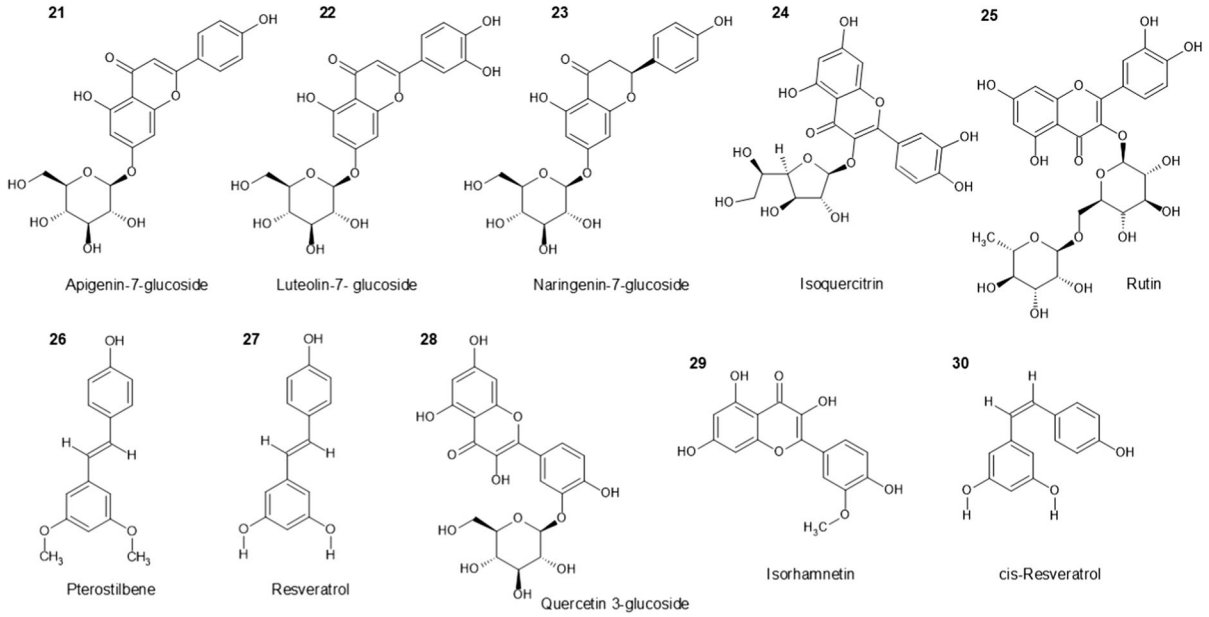


Fig. 4 Chemical structures of flavonoid derivatives, stilbenes and other phenolic compounds identified in the fruit extract of *O. bataua.* ACD/ChemSketch

relatively low or undetectable across all vegetative organs (Table 5).

Extracts from *O. bataua* organs exhibited a high diversity of secondary metabolites. Metabolic profiling was conducted on defatted fruit extracts using HPLC–MS for identification, alongside the quantification of fatty acids and carotenoids. Specifically, twenty-four compounds were identified in specimens from the Peruvian Amazon via UHPLC-MS, comprising nine phenolic acids, four C-glycosyl flavonoids, two flavonols, one flavanol, three anthocyanins, and five resveratrol derivatives. Among the anthocyanins, cyanidin 3-O-(6-*O*-p-coumaroyl) glucoside, pelargonidin 3-*O*-glucoside, and cyanidin 3-*O*-rutinoside were identified. Their identities were confirmed through co-elution with authentic standards and comparison with literature data. Flavonoids included quercetin 3-*O*-glucoside, isorhamnetin 3-*O*-glucoside,

Table 5 Bioactive compounds according to the vegetative parts of the species *O. bataua*

Organ	Extract	t-Res	AsA	α-Toc	o-Toc	References
Leaves	–	–	–	–	–	–
Fruit/pulp	–	NR	NR	78.5%	21.5%	(Darnet et al. 2011)
	Acetone/Aqueous	NR	ND	6.1 ± 0.1	3.5 ± 0.1	(Rezaire et al. 2014)
	–	NR	NR	8.19 ± 0.08^{II}	NR	(Vargas-Arana et al. 2022)
	Ethanolic	1.94 ± 0.10	0.12 ± 0.00	NR	NR	(Méndez-Durazno et al. 2023)
Oil	–	–	–	–	–	–
Seed	Ethanolic	12.33 ± 0.01	0.00 ± 0.00	NR	NR	(Méndez-Durazno et al. 2023)
Peel	Ethanolic	7.98 ± 0.01	0.00 ± 0.00	NR	NR	(Méndez-Durazno et al. 2023)
Root	–	–	–	–	–	–

trans-resveratrol (t-Res); Ascorbic acid (AsA); Alpha-tocopherol (α-Toc); Other tocopherols (o-Toc); Dry weight (DW). Units are expressed based on dry weight (g^{-1} DW or 100 g^{-1} DW). Bellavista (I); Hacienda Concepción (II); Jenaro Herrera (III); Contamana (IV); Allpahuayo Mishana (V); San Lorenzo (VI); Atalaya (VII); Palestina (VIII); Tunaants (IX); Not reported (NR); Undetected (ND)

naringenin 5-*O*-glucoside, luteolin 6-*C*-glucoside (isoorientin), apigenin 6-*C*-glucoside (isovitexin), apigenin di-*C*-glucoside, and vicenin-2. Resveratrol derivatives were identified as methoxyresveratrol diglucoside, methoxyresveratrol rutinoside, resveratrol diglucoside, and a hydroxylated derivative of the latter. Finally, identified phenolic acids included quinic acid, 1-*O*-sinapoyl-glucoside, syringic acid glycoside, caffeoylquinic acid isomers (including chlorogenic acid), 3,5-dicaffeoylquinic acid, 3-caffeoyl-5-feruloylquinic acid, methyl chlorogenate, and 4-*O*-(3'-*O*-glucopyranosyl)-caffeoylquinic acid (Fig. 5; Table 6) (Vargas-Arana et al. 2022).

Another study identified a total of 42 chemical compounds, including phenolics, terpenoids, steroids, alkaloids, coumarins, polyacetylenes, peptides, and saponins. The majority of the phenolic compounds notably 5-*O*-methyl shanciguol, gomisin G, and blestritin C were localized in the pulp (Fig. 7) (Méndez-Durazno et al. 2023). Compound identification in *O. bataua* root and leaf extracts was performed via LC-MSn. Fourteen essential bioactive compounds were identified in the leaf extracts and six in the roots, with structures proposed based on LC-MSn fragmentation patterns. In both root and leaf extracts, three peaks corresponded to caffeoylquinic acids (CQA): compounds 1, 2, and 3 were assigned as 3-CQA, 4-CQA, and 5-CQA, respectively. Additionally, the root extracts contained three peaks corresponding to caffeoylshikimic acids (CSA), where compound 4 was identified as 4-CSA and compound 5 as 5-CSA (Fig. 6); however, the exact structure of compound 6 remained undetermined due to inconclusive data. Finally, the leaf extracts contained eleven flavone derivatives exhibiting hexose residues, confirmed to be 6-*C*-glucosyl apigenin (Fig. 5) (Leba et al. 2016).

Nine compounds exhibited fragmentation patterns characteristic of di-*C*-glycosyl flavones, indicative of apigenin derivatives. Compound 7, a hexose derivative, was consistent with 6,8-di-*C*-hexosyl apigenin, while compounds 8 and 9 suggested 6,8-di-*C*-hexosyl apigenin sulfates. Five peaks (10, 12, 14, 15, and 16) displayed residues characteristic of pentose and hexose moieties, suggesting 6,8-di-*C*-pentosyl-hexosyl apigenin derivatives. Specifically, compounds 12 and 16 were identified as 6-*C*-pentosyl-8-*C*-hexosyl apigenin isomers, whereas compounds 10, 14, and 15 were assigned as 6-*C*-hexosyl-8-*C*-pentosyl apigenin isomers. Compounds 11 and 13 exhibited flavone characteristics consistent with *C*-glycosyl luteolin derivatives, identified as 8-*C*-glucosyl luteolin and 6-*C*-glucosyl luteolin, respectively; these identities

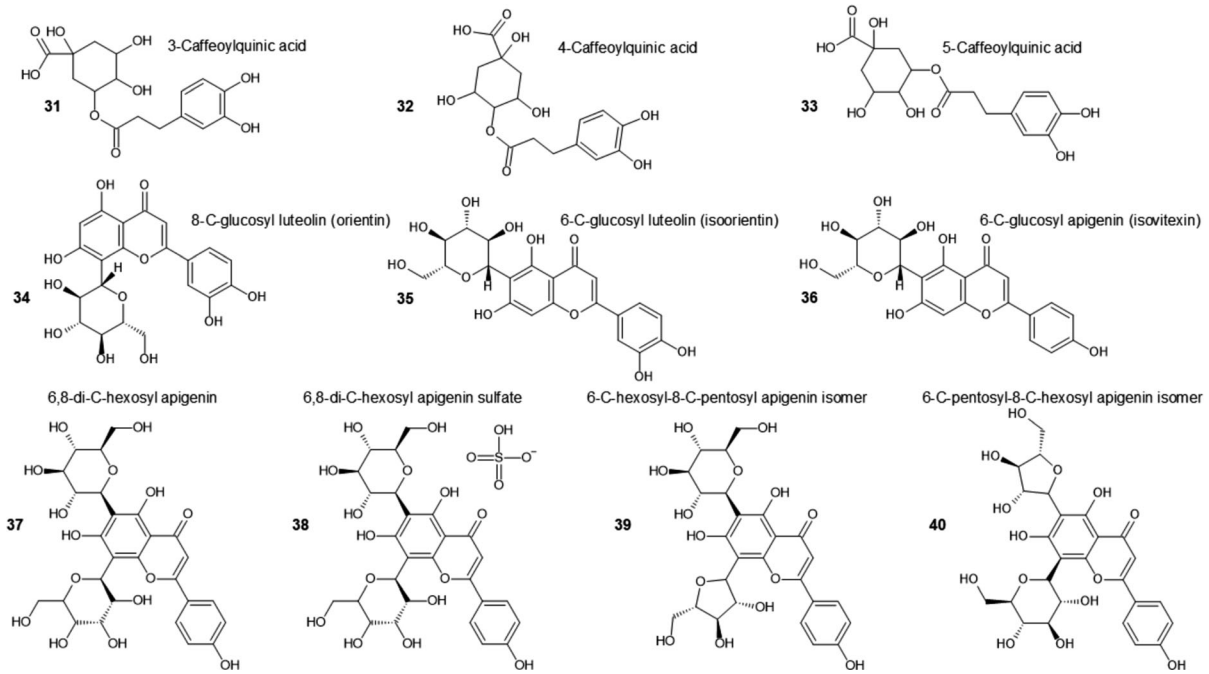


Fig. 5 Chemical structures of compounds identified in the leaves extract of *O. bataua.* ACD/ChemSketch

Table 6 Compound identified in fruit/pulp the species *O. bataua* by different chromatographic methods

Compound name	Molecular formula	Method	References
1-*O*-Sinapoylglucoside[I–IX, a]	$C_{17}H_{22}O_{10}$	UHPLC-ESI MS/MS	(Vargas-Arana et al. 2022)
4-*O*-(30′-*O*-Glucopyranosyl)-caffeoyl quinic acid[VIII, a]	$C_{22}H_{28}O_{14}$		
Cyanidin 3-*O*-(6-*O*-p coumaroyl) glucose[I–IX,a]	$C_{30}H_{27}O_{13}$		
Naringenin-5-*O*-glucoside[III,V–IX,a]	$C_{21}H_{22}O_{10}$		
Methoxyresveratrol diglucose[III,VI–IX,b]	$C_{27}H_{33}O_{14}$		
Methoxyresveratrol rutinose[VIII,IX,b]	$C_{27}H_{33}O_{13}$		
Resveratrol diglucose[I–IX,b]	$C_{26}H_{31}O_{14}$		
Hydroxyresveratrol dihexoside[b]	–	UPLC-API-IT-MSn	(Rezaire et al. 2014)
Resveratrol dihexoside[b]	–		

Ultra-high performance liquid chromatography-electrospray ionization tandem mass spectrometry (UHPLC-ESI MS/MS); Ultra-Performance liquid chromatography, diode array detector with atmospheric pressure ionization coupled tandem mass spectrometry (UPLC-DAD-API-IT-MSn); Phenolic compounds (a); Resveratrol derivatives (b); Bellavista (I); Hacienda Concepción (II); Jenaro Herrera (III); Contamana (IV); Allpahuayo Mishana (V); San Lorenzo (VI); Atalaya (VII); Palestine (VIII); Tunaants (IX

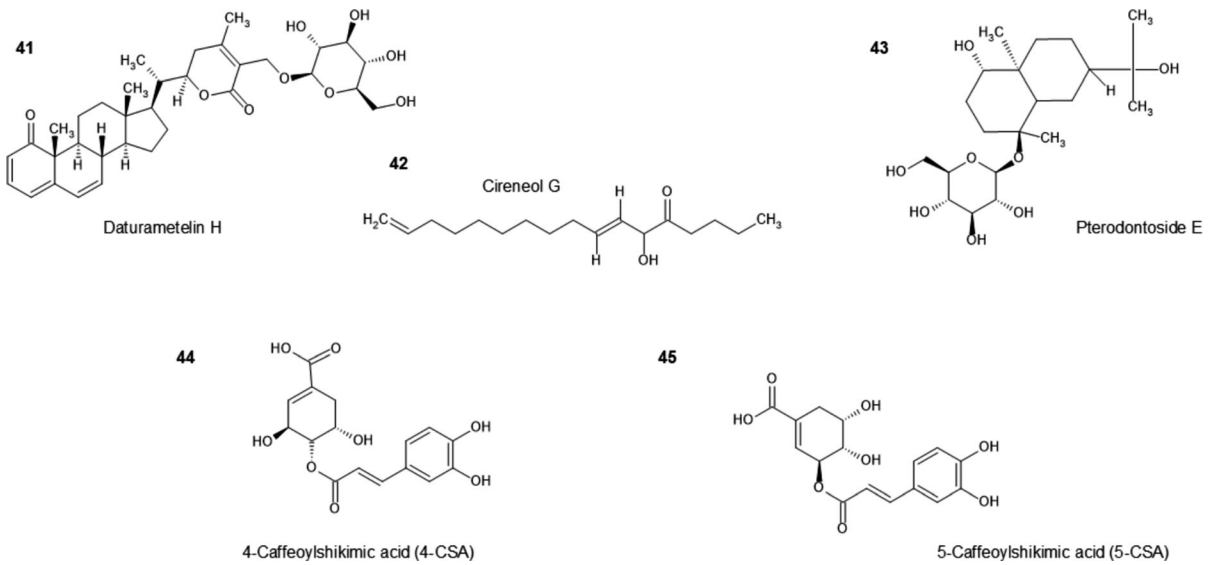


Fig. 6 Chemical structures of compounds identified in the seed, peel and roots extract of *O. bataua.* ACD/ChemSketch

were confirmed using synthetic standards. *C*-glycosyl flavones and caffeoylquinic acids (CQAs) were the primary constituents of *O. bataua* leaf extracts. Since flavonoid profiles including aglycone type, sugar moieties, and substitution patterns—serve as valuable taxonomic markers, the predominance of *C*-glycosyl apigenin (60–80% of total flavones) suggests its potential as a phytochemical marker for the species. Acetone and methanolic leaf extracts provided the highest yields of flavones and CQAs. In contrast, root extracts presented a mixed CQA-CSA profile, with 5-CQA as the major component. Consequently, caffeoylshikimic acids (CSAs) could serve as chemical markers to differentiate *O. bataua* roots from those of related species, such as *Oenocarpus bacaba* (Leba et al. 2016) (Fig. 6).

The UPLC profile of the acetone/aqueous "patauá" fruit extract revealed eleven major peaks. Peaks 1, 5, and 6 exhibited characteristics of hydroxycinnamic acids and were provisionally identified as chlorogenic

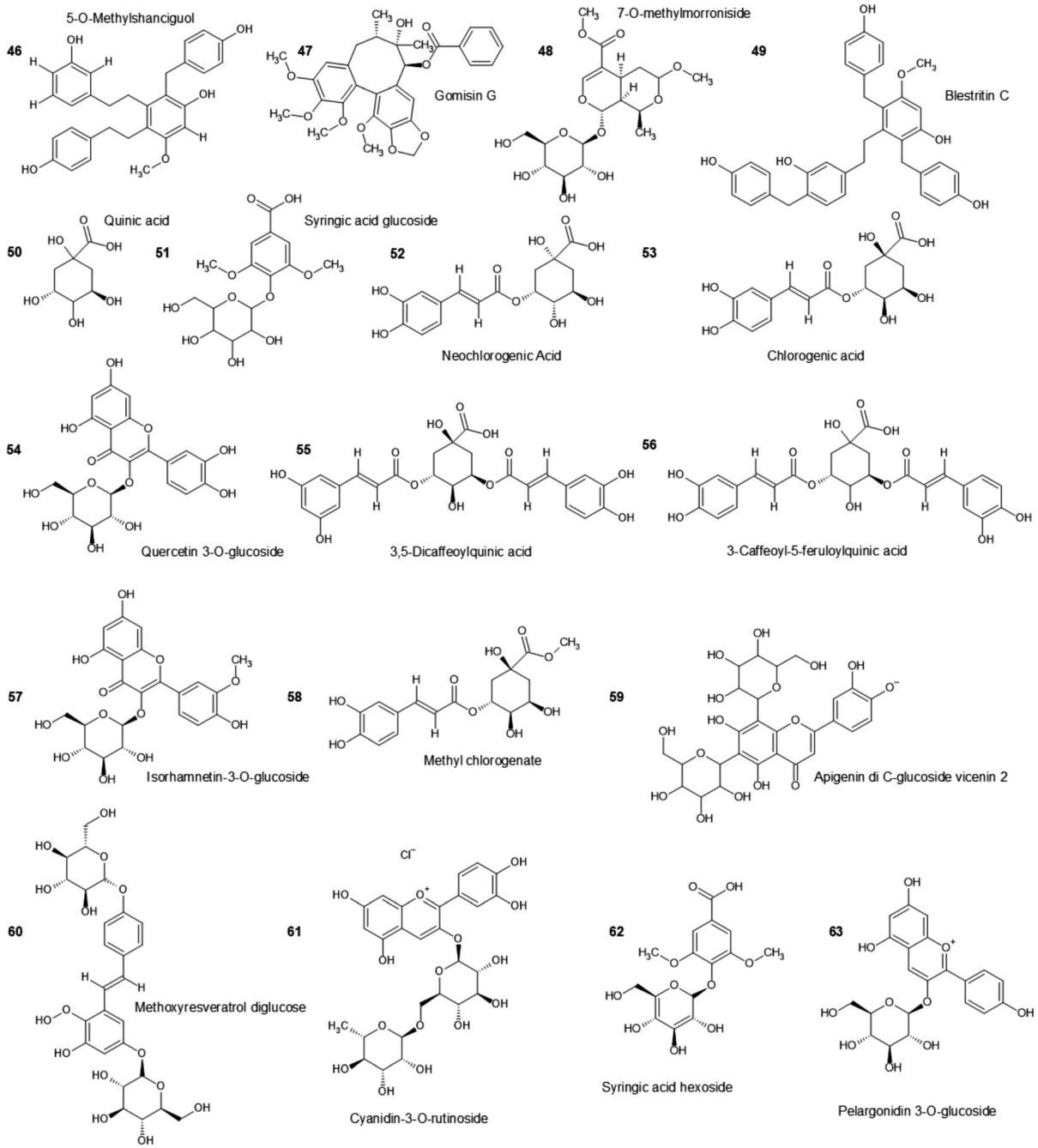


Fig. 7 Chemical structures of compounds identified in the fruit/pulp extract of *O. bataua.* ACD/ChemSketch

acid and its isomers. Based on specific fragmentation patterns, peak 1 was assigned to 3-*O*-caffeoylquinic acid, peak 5 to 5-*O*-caffeoylquinic acid, and peak 6 to 4-*O*-caffeoylquinic acid. Peak 2 showed typical hydroxybenzoic acid features, consistent with syringic acid, while peaks 2 and 3 were provisionally identified as syringic acid hexoside isomers. Peaks 4, 7, 8, 9, and 11 appear to belong to the same polyphenol family, presumably stilbenes, with aglycones corresponding to hydroxylated resveratrol derivatives, such as piceatannol. Specifically, peak 4 was assigned as a dihexoside of a hydroxylated resveratrol derivative,

and peak 7 as a resveratrol dihexoside. Peaks 8 and 9 likely correspond to dihexoside isomers of methoxyresveratrol, such as rhapontigenin or isorhapontigenin, while peak 11 is characteristic of trans-resveratrol. Finally, peak 10 was identified as an anthocyanin, specifically cyanidin 3-*O*-rutinoside. *O. bataua* possesses a unique polyphenolic profile rich in stilbenes, caffeoylquinic acids, hydroxybenzoic acid derivatives, and procyanidins—distinguishing it from other Oenocarpus species (Rezaire et al. 2014).

Antioxidant-monitored isolation from the methanolic extract of "patauá" pulp, conducted via thin-layer chromatography, led to the identification of the stilbene piceatannol (3,3',4,5'-trans-tetrahydroxystilbene or 4-[(1E)-2-(3,5-dihydroxyphenyl)ethenyl]-1,2-benzenediol) (Hidalgo et al. 2016). This represents the first and, to date, the only report of its isolation from this species. Piceatannol possesses documented pharmacological properties, including wound healing, anti-aging, antioxidant, anti-acne, and skin-lightening effects (Krambeck et al. 2023). In general, stilbenoids exhibit a broad range of biological activities, such as cardioprotection, neuroprotection, anti-diabetic effects, depigmentation, anti-inflammation, and cancer prevention. While resveratrol remains the most extensively studied stilbenoid, information regarding the potential of less common derivatives remains limited. Consequently, further research is essential to evaluate the beneficial effects of various other stilbenoids (Akinwumi et al. 2018).

Phytochemicals can be utilized to optimize the treatment of various health conditions and possess the potential to synergistically enhance conventional therapies. A significant advantage of these natural compounds is their generally favorable safety profile, which makes them attractive therapeutic alternatives. In essence, phytochemicals hold immense potential as agents against diverse pathologies. However, progress in this field requires more than isolated identification and characterization; it must also address bioavailability, drug development viability, regulatory safety, and challenges in standardization and scalability. Consequently, further research is essential to fully elucidate their mechanisms of action and clinical applications. Future studies should focus on optimizing their efficacy through combination therapies and the exploration of novel compounds. By doing so, the true potential of phytochemicals can be realized in the development of safe, effective, and personalized healthcare solutions derived from natural sources (Aljabali et al. 2025).

Biological properties

Antioxidant activity

Antioxidants have garnered significant research interest due to their versatile applications in the cosmetic, pharmaceutical, and food industries. Their protective action is associated with a reduced risk of various conditions linked to oxidative stress induced by reactive oxygen species (ROS). These include chronic pathologies such as cancer, DNA damage, cardiovascular disorders, cellular senescence, and neurodegenerative diseases notably Parkinson's and Alzheimer's (Pandey and Rizvi 2009). Antioxidant compounds inhibit oxidative processes through multiple pathways, either by terminating radical chain reactions via direct scavenging or by chelating metal ions that catalyze oxidation (Ou et al. 2002). Assessing antioxidant potential is routinely performed using in vitro bioassays, such as ORAC, DPPH, and FRAP. The simultaneous employment of these assays is essential due to the chemical complexity of biological systems; a multiparametric approach is required to account for diverse mechanisms such as electron or hydrogen atom transfer and substrate specificity toward distinct free radicals (Brand-Williams et al. 1995; Benzie and Strain 1996; Ou et al. 2002). In human cells, the primary mediators of oxidative stress originate from aerobic metabolism, yielding Reactive Oxygen Species (ROS) and Reactive Nitrogen Species (RNS). Prominent among these molecules are the superoxide radical, hydrogen peroxide, and hydroxyl radical, alongside nitrogenous species like nitric oxide and peroxynitrite (Kumar and Pandey 2015; Valko et al. 2007).

Natural products encompass various phytochemicals with antioxidant properties, including phenolic compounds, alkaloids, carotenoids, vitamins, and fatty acids. Among these, *O. bataua* has demonstrated promising antioxidant capacity (Leba et al. 2014, 2016; Méndez-Durazno et al. 2023; Rezaire et al. 2014; Vargas-Arana et al. 2022). In a study evaluating the in vitro antioxidant potential of ripe *O. bataua* fruit (lyophilized pulp; Table 7), researchers revealed high antioxidant capacity and suggested that

Table 7 Antioxidant activity of different *O. bataua* parts extracts determined by multiple chemical assays

Sample type	DPPH	TEAC/ABTS	FRAP	ORAC	KRL	AI_{50}	EI	References
E. AC. pulp	2292.5 ± 122.77	2471.5 ± 22	1869.9 ± 111.1	1626.7 ± 13.9	2553.8 ± 18	NR	NR	(Rezaire et al. 2014)
E. AQ. pulp	424 ± 3	NR	1,8 ± 0,1	2189 ± 163	NR	NR	NR	(Leba et al. 2014)
E. AC. pulp	1325 ± 99	NR	2,7 ± 0,2	2132 ± 104	NR	NR	NR	
E. M. pulp	2054 ± 100	NR	4,8 ± 0,1	3708 ± 359	NR	NR	NR	
E. M. pulp	115.00 ± 0,11	NR	584.9 ± 5,3	NR	NR	NR	NR	(Hidalgo et al. 2016)
E. M. seed	7,0 ± 0,1	NR	1791.4 ± 3,2	NR	NR	NR	NR	
E. AQ. roots	60.9 ± 18.7	NR	128 ± 20	218 ± 28	NR	NR	NR	(Leba et al. 2016)
E. AC. roots	288.7 ± 12.7	NR	559 ± 44	720 ± 76	NR	NR	NR	
E. M. roots	227.7 ± 33.9	NR	418 ± 52	627 ± 68	NR	NR	NR	
E. AQ. leaflets	68.9 ± 10.9	NR	138 ± 28	229 ± 42	NR	NR	NR	
E. AC. leaflets	461 ± 35.8	NR	729 ± 23	1203 ± 168	NR	NR	NR	
E. M. leaflets	197.4 ± 39	NR	327 ± 54	569 ± 38	NR	NR	NR	
E. E. pulp	478.94 ± 4.85	NR	NR	NR	NR	1.56 ± 0.08	11.92 ± 0.05	(Méndez-Durazno et al. 2023)
E. E. bark	654.56 ± 0.94	NR	NR	NR	NR	1.47 ± 0.07	15.51 ± 0.16	
E. E. seed	589.44 ± 5.29	NR	NR	NR	NR	1.52 ± 0.10	12.29 ± 0.27	
E. H. pulp	NR	NR	40	11.181	NR	NR	NR	(Lima et al. 2025)

2,2-diphenyl-1-picrylhydrazyl (DPPH) expressed as TEq μmol/g DE or CS_{50} μg/mL; 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) expressed as TEq μmol/g DE; Ferric Reducing Antioxidant Power (FRAP) expressed as TEq μmol/g DE, μmol Fe (II) Eq/g, or mg GAE/100 g; Oxygen Radical Absorbance Capacity (ORAC) expressed as TEq μmol/g DE or μmol AAE/100 g; Kit Radicaux Libres (KRL) expressed as TEq μmol/g DE; Antioxidant Index 50 (AI_{50}) mg mL^{-1}); Electrochemical Index (EI) μA V^{-1}. Dry Extract (DE); Trolox Equivalent (TEq); Ascorbic Acid Equivalent (AAE); Gallic Acid Equivalent (GAE). 70% acetone extract (E. AC.); Aqueous extract (E. AQ.); 70% methanolic extract (E. M.); Ethanolic extract (E. E.); 50% hydroalcoholic extract (E.H.); Bellavista (I); Hacienda Concepción (II); Jenaro Herrera (III); Contamana (IV); Allpahuayo Mishana (V); San Lorenzo (VI); Atalaya (VII); Palestina (VIII); Tunaants (IX); Not reported (NR)

Oxygen Radical Absorbance Capacity (ORAC) and Kit Radicaux Libres (KRL) assays effectively reflect antioxidant effects on biological systems. This study utilized the free radical generator AAPH, which is recognized as a reliable source of biological free radicals (Prior et al. 2003). Furthermore, the KRL assay, by using whole blood, highlights how extracts interact with both cellular and plasma antioxidant defenses, thus closely approximating biological conditions (Rezaire et al. 2014). According to Kang et al. (2010), açaí was the first Amazonian palm fruit to be extensively investigated, showing significant in vitro antioxidant potential; the authors further emphasize that this activity is largely attributable to phenolic compounds, particularly anthocyanins and other flavonoids.

In the study by Rezaire et al. (2014), *O. bataua* exhibited slightly higher antioxidant activity than açaí in the TEAC and FRAP assays (classified as robust results), whereas significantly lower values were recorded in the ORAC and KRL tests (regarded as exploratory data). Conversely, both extracts showed comparable outcomes in the DPPH assay and equivalent total phenolic contents. The authors suggest that the discrepancies among the various antioxidant evaluation methods, coupled with the lack of a direct correlation between antioxidant activity and total polyphenol content, may stem from the presence of other constituents such as sugars, ascorbic acid, and additional reducing compounds which can interfere with both the Folin–Ciocalteu assay and the antioxidant tests (Rezaire et al. 2014).

In vitro DNA cleavage assays offer greater biological relevance compared to purely chemical methods, establishing themselves as effective tools for the rapid screening of compounds with potential in vivo antioxidant activity (Leba et al. 2014). Among the in vitro methodologies for evaluating genomic damage, the assay based on the Fenton reaction stands out for mimicking the endogenous generation of hydroxyl radicals (•OH) via iron catalysis (Santanaraj et al. 2017). In this system, the high reactivity of •OH induces a conformational transition of plasmid DNA from its supercoiled form to open circular and linear isoforms, resulting in distinct electrophoretic mobility profiles (Kitts et al. 2000). However, the efficacy of this damage depends on the composition of the reaction medium; iron ions can interact directly with DNA, while organic solvents tend to mitigate the oxidative process (Flemmig and Arnhold 2007). Discussions persist regarding the roles of iron and EDTA in degradation kinetics, as the stoichiometry among iron, EDTA, and H_2O_2 is a determining factor for the reaction outcome (Engelmann et al. 2003).

Researchers evaluated the ability of various *O. bataua* extract concentrations to protect a biological matrix, such as DNA, from oxidative stress. They compared these findings to chemical assays using the DNA nicking assay for non-site-specific •OH scavenging activity (Leba et al. 2014). The study demonstrated that aqueous and acetone extracts of *O. bataua* protected against DNA damage, following optimization of the iron/EDTA ratio and solvent concentration. Interestingly, extracts with lower Ferric Reducing Antioxidant Power (FRAP) specifically the aqueous and 70% acetone extracts exhibited greater protection in the DNA assay (Table 7). The authors suggest that this behavior occurs because extracts with high Fe^{3+} to Fe^{2+} reduction capacity may paradoxically induce more hydroxyl radicals, thereby accelerating DNA degradation. These findings reinforce the necessity of employing multiple in vitro and in vivo assays to comprehensively evaluate the antioxidant properties of natural extracts (Leba et al. 2014). While the DNA cleavage assay is a robust methodology for assessing antioxidant and pro-oxidant effects on physiologically relevant targets, investigating iron-coordination (binding) capacity is imperative for a reliable understanding of these properties, as the interaction between extracts and metal ions is critical in modulating oxidative damage to genetic material (Leba et al. 2014).

A separate study evaluated the antioxidant potential of methanolic extracts from *O. bataua* pulp and seeds using the DPPH radical scavenging and FRAP assays, reporting high activity for both. The authors noted a strong correlation between total phenolic content and antioxidant efficacy across both methods. Notably, the seed extract exhibited the highest phenolic concentration, the greatest reducing power via FRAP, and the lowest IC_{50} for DPPH scavenging (Table 7) (Hidalgo et al. 2016). These results demonstrate that *O. bataua* possesses a robust antioxidant capacity directly linked to its phenolic profile. The biological efficacy of such extracts is governed by the chemical architecture of these metabolites, where aromatic rings and hydroxyl groups facilitate the neutralization of oxidants (Huang et al. 2005). In the DPPH assay, the seed extract's superior potency indicated by its low IC_{50} suggests

efficient hydrogen atom donation through the Hydrogen Atom Transfer (HAT) mechanism (Brand-Williams et al. 1995). This rapid radical stabilization implies that "patauá" phenolics possess low O–H bond dissociation energy, enabling the early termination of free radical chain reactions. Concurrently, FRAP data confirmed the seeds' superior reducing power, operating through the Single Electron Transfer (SET) mechanism to reduce ferric (Fe^{3+}) to ferrous (Fe^{2+}) ions (Benzie and Strain 1996).

Researchers also evaluated the antioxidant activity of aqueous, acetonic, and methanolic extracts from the roots and leaflets of *O. bacaba* and *O. bataua* using ORAC, DPPH, and FRAP assays, as well as the Cellular Antioxidant Activity (CAA) assay in normal human dermal fibroblasts (NHDF) (Leba et al. 2016). The results demonstrated that the extracts were potent antioxidants across the DPPH, FRAP, and ORAC assays, with Oenocarpus leaflet extracts exhibiting significantly higher antioxidant activity than root extracts (Table 7). Regarding the CAA assay, the EC_{50} values for *O. bataua* extracts ranged from 13.8 ± 2.3 to 65.7 ± 19.8 µg/mL for leaflets and 21.7 ± 3.2 to 71.9 ± 5.7 µg/mL for roots, corroborating the high antioxidant potential revealed by in vitro chemical assays. The authors suggest that Oenocarpus extracts may influence CAA primarily through a peroxyl radical scavenging mechanism the same principle as the ORAC assay since the highest antioxidant capacity in the chemical tests was obtained using this specific method (Leba et al. 2016).

O. bataua and *O. bacaba* leaf extracts and to a lesser extent, root extracts demonstrated high potency in chemical antioxidant assays (DPPH, FRAP, and ORAC), which translated effectively to the cellular antioxidant activity (CAA) in normal human dermal fibroblasts (Table 7). These findings suggest that the extracts operate through a free radical scavenging mechanism within a cellular environment. Oenocarpus leaves were characterized by a complex flavonoid profile, primarily composed of *C*-glycosyl apigenin derivatives; these compounds are rare among Arecaceae species and serve as valuable phytochemical markers for the genus. Hydroxycinnamic acids were identified in both organs: caffeoylquinic acids (CQAs) in the leaves, and both CQAs and caffeoylshikimic acids in the roots. Specifically, CQAs and flavones were the primary drivers of antioxidant activity in Oenocarpus roots and leaves, respectively. The antioxidant capacity of the leaf extracts was notably promising, matching or exceeding that of Euterpe oleracea berries widely recognized as a 'superfruit.' These extracts represent a potential novel, non-cytotoxic source of antioxidants for dermatological and pharmaceutical applications (Leba et al. 2016).

The established correlation between ORAC and Cellular Antioxidant Activity (CAA) assays suggests that Oenocarpus extracts exert their bioactivity predominantly through peroxyl radical scavenging, mirroring the intrinsic mechanism of the ORAC method (Girard-Lalancette et al. 2009). Should the polyphenolic fraction of these extracts demonstrate permeability across the cell membrane, these findings would hold significant weight in dermatology, given the pivotal role of dermal fibroblasts in maintaining structural integrity and facilitating connective tissue repair. Nevertheless, a more comprehensive investigation into the in vitro antioxidant and anti-inflammatory potential of these extracts is essential, as oxidative stress remains a critical modulator of numerous pro-inflammatory pathways (Reuter and Gupta 2010). In summary, robust evidence indicates that Oenocarpus extracts operate via multiple mechanisms of action, which are dictated by the analytical system employed and are intrinsically linked to the samples' polyphenolic profiles (Leba et al. 2016). Furthermore, the data underscore the capacity of these constituents to mitigate free-radical-mediated damage within a cellular environment (Leba et al. 2016).

The ORAC assay exhibits superior analytical sensitivity compared to alternative methods, as it relies on the fluorometric monitoring of molecular probe degradation induced by peroxyl radicals. Owing to its robustness and capacity to mimic lipid oxidation dynamics, this methodology has become a standardized benchmarking tool within the food and fruit industries for quantifying antioxidant potential. Conversely, the quantification of phenolic compounds via the Folin-Ciocalteu method, alongside ABTS and DPPH radical scavenging assays, operates primarily through Single Electron Transfer (SET) or mixed mechanisms (Vargas-Arana et al. 2022).

Other researchers examined the antioxidant activity of "patauá" fruits (*O. bataua*) from nine different locations across three genetic groups in the Peruvian Amazon using ABTS, DPPH, and ORAC assays (Table 8). Most samples demonstrated excellent antioxidant capacity, as reported by Vargas-Arana

et al. (2022). The authors noted variations in the correlations between these assays, suggesting that such discrepancies stem from the distinct chemical nature of each test. The robustness of *O. bataua*'s antioxidant profile is underscored by its consistent performance across diverse populations, where the majority of samples exhibited high efficacy. These findings corroborate the premise that the species possesses an intrinsic capacity for radical neutralization through mixed hydrogen and electron transfer mechanisms, independent of local genetic variability (Vargas-Arana et al. 2022).

Antioxidant properties have been documented in the ethanolic extracts of *O. bataua* seeds, pulp, and epicarp (peel) using DPPH, Antioxidant Index 50 (AI_{50}), and Electrochemical Index (EI) assays (Table 7). A strong linear correlation exists between electrochemical profiles and DPPH-measured antioxidant activity (Méndez-Durazno et al. 2023), suggesting that both methods capture the same electron transfer phenomena. The EI serves as a thermodynamic biomarker of polyphenol reactivity, validating electroanalysis as a robust, complementary tool to conventional colorimetric assays for characterizing Amazonian fruits (Ziyatdinova and Kalmykova 2023). Furthermore, evaluating different *O. bataua* tissues reinforces the species' chemical versatility. While DPPH and the AI_{50} parameter confirm the efficacy of extracts in neutralizing free radicals via hydrogen atom transfer, the EI provides compelling thermodynamic evidence of their reducing potential. The detected electrochemical activity indicates that these phenolic compounds possess low oxidation potentials, which facilitates electron transfer and ensures effective defense against reactive species across various cellular environments. Notably, the presence of such activity in the epicarp and seeds suggests that "patauá" processing by-products retain significant bioactive fractions, with reducing properties comparable or superior to those of the pulp.

The high antioxidant capacity of *O. bataua* is mechanistic, rooted in the density of its phenolic compounds, whose specific molecular structures confer essential reducing properties for mitigating reactive oxygen species (ROS) (Robles-Sánchez et al. 2011; Hussain et al. 2016). The efficacy of these metabolites lies in their ability to neutralize free radicals before they trigger oxidative damage to critical biomolecules, including proteins, DNA, and membrane lipids. Such early neutralization is vital for cellular stability, as persistent oxidative stress is strongly linked to the induction of somatic mutations and neoplastic transformation (Hussain et al. 2016). The robustness of *O. bataua*'s antioxidant profile is further corroborated by advanced electrochemical analyses. Consequently, the action of "patauá" phenolics transcends mere radical scavenging, functioning as a mechanism for genomic and functional protection against oxidation-mediated pathologies. These data underscore the potential of this underutilized Amazonian fruit as a functional food rich in bioactive and antioxidant constituents (Méndez-Durazno et al. 2023).

A recent study evaluated the impact of simulated human digestion on the phytochemical properties and antioxidant capacity of "patauá" pulp extract in human cells and plasma (Lima et al. 2025). Antioxidant capacity was measured using Oxygen Radical Absorbance Capacity (ORAC) and Ferric Reducing Antioxidant Power (FRAP) assays, both of which revealed a significant decrease in activity following digestion (Table 7). These findings provide robust evidence that, although "patauá" pulp is a potent source of polyphenols in vitro, its antioxidant properties are negatively affected by the digestive process (Lima et al. 2025). This reduction in performance is attributed to the intrinsic instability of phenolic constituents under gastrointestinal physiological conditions. During digestion, the transition between gastric and enteric environments promotes oxidation, methylation, and hydrolysis, altering the molecular configuration of the native polyphenols (Chen et al. 2020). Such structural modifications result in the loss or blocking of reactive hydroxyl groups, directly compromising the extract's ability to operate via electron transfer (reducing power) or hydrogen atom transfer (radical scavenging) (Chen et al. 2020; Soares et al. 2025). Consequently, the biotransformation of these compounds into less active secondary metabolites explains the decline in ORAC and FRAP indices, underscoring that the chemical integrity of "patauá" antioxidants is partially compromised during digestive metabolism (Chen et al. 2020; Soares et al. 2025).

Notably, this study establishes a correlation between total phenolic content (TPC) and antioxidant activity, highlighting a link not commonly reported in research on this species. These results indicate that *O. bataua* extracts operate through distinct modes of

action across various antioxidant assays, with activity inherently linked to their polyphenolic composition, which was investigated via UV and LC-MSn for further understanding. In root extracts, high values in the DPPH, FRAP, ORAC, and TPC assays (negative PC1 values) correlated strongly with high 3-CQA and 4-CQA content, rather than with CSA content. Despite the high CSA concentration in *O. bataua* roots, their antioxidant activity was merely equivalent to that of *O. bacaba* roots. Consequently, a high CQA content was identified as the primary driver of antioxidant activity in Oenocarpus roots. Identifying the main drivers in Oenocarpus leaves was less clear from the PCA results; overall, it appears that some of the flavones, rather than CQAs, correlated with high antioxidant activity (Leba et al. 2016).

Scientifically, the full potential of *Oenocarpus bataua* fruit remains underexplored. Research has demonstrated that "patauá" possesses significant in vitro chemical and biological antioxidant activities, primarily attributed to its polyphenolic and vitamin content. When compared to açaí (*Euterpe oleracea*), "patauá" exhibited superior antioxidant activity in TEAC and FRAP assays, equivalent capacity in the DPPH assay, but lower performance in ORAC and KRL tests. These discrepancies may stem from the higher concentration of vitamins (notably ascorbic acid) and anthocyanins found in açaí. Nevertheless, compared to other antioxidant-rich berries, *O. bataua* displays high activity, positioning it as a potential "superfruit". The presence of various polyphenols such as stilbenes, phenolic acids, and an exceptionally high concentration of condensed tannins likely drives this antioxidant profile. However, further investigations into structural elucidation and biological evaluation are essential to promote the valorization of "patauá" in the nutritional, pharmaceutical, and cosmetic sectors, similar to *E. oleracea* (Rezaire et al. 2014).

Antimicrobial activity

The species *O. bataua* also exhibits antimicrobial activity (Table 9), a property of increasing relevance given that antimicrobial resistance (AMR) poses a severe threat to global health. AMR constitutes a significant public health challenge, with its environmental dissemination already widely documented (Ayobami et al. 2022; Getahun et al. 2022). Consequently, the emergence of multidrug-resistant (MDR) microorganisms has intensified the urgency for novel therapeutic approaches to counteract resistance mechanisms (Dar et al. 2022). The prevalence of MDR in clinically significant pathogens including bacteria, fungi, viruses, and protozoa has become a burgeoning global concern, primarily driven by the persistent and inappropriate use of antimicrobial agents (Velazquez-Meza et al. 2022; Zhu et al. 2022).

In this context, the antibacterial potential of plant-derived secondary metabolites has been the subject of intensive research. These compounds provide a natural repository of molecules with diverse and complex chemical architectures, exhibiting a broad spectrum of efficacy against various human pathogens and serving as templates for the development of novel antimicrobial agents. Consequently, the antimicrobial activity of *O. bataua* is increasingly relevant, meeting the growing demand for natural alternatives in light of the widespread resistance of several pathogens to existing drugs (Arias and Murray 2012; Gould et al. 2012).

Researchers evaluated the antimicrobial activity of methanolic extracts from *O. bataua* (Peruvian Amazon) using in vitro Minimum Inhibitory Concentration (MIC) assays against 36 microbial strains across 21 species. *O. bataua* demonstrated efficacy against non-enterobacterial Gram-negative bacteria, Gram-positive cocci, Candida spp., and various other microorganisms (Table 9). The study suggests that bioactive constituents in the fruit including anthocyanins, condensed tannins, stilbenes, and phenolic acids play a pivotal role in this antimicrobial activity. Furthermore, comparing the activity of 40 plant species under a standardized methodology enabled the definition of antimicrobial profiles for standardized extracts, thereby supporting their traditional medicinal use. This comparative analysis under identical test conditions may facilitate the discovery of novel chemical classes of antimicrobial agents effective against multidrug-resistant (MDR) bacteria. Notably, this was the first study to evaluate these plants against an extensive array of pathogens using a single, standardized MIC protocol. Observations that resistant *K. pneumoniae* strains exhibited greater sensitivity to the extracts than non-resistant strains suggest that these extracts operate through distinct and complementary modes of action compared to conventional antibiotics (Roumy et al. 2015).

Table 8 Antioxidant activity of different *O. bataua* fruit extracts determined by multiple chemical assays

Sample type	DPPH	TEAC/ABTS	FRAP	ORAC	KRL	AI_{50}	EI	References
Fruit extractt^{I}	1510.94 ± 73.90	870.57 ± 16.05	NR	869.74 ± 17.75	NR	NR	NR	(Vargas-Arana et al. 2022)
Fruit extract^{II}	1402.18 ± 20.51	748.81 ± 14.43	NR	521.71 ± 11.87	NR	NR	NR	
Fruit extract^{III}	1557.51 ± 17.05	892.65 ± 11.55	NR	715.81 ± 6.47	NR	NR	NR	
Fruit extract^{IV}	1356.08 ± 17.93	831.51 ± 14.82	NR	687.94 ± 7.65	NR	NR	NR	
Fruit extract^{V}	2082.27 ± 41.10	1803.72 ± 20.86	NR	921.30 ± 3.06	NR	NR	NR	
Fruit extract^{VI}	962.21 ± 13.46	804.64 ± 15.80	NR	1222.28 ± 20.88	NR	NR	NR	
Fruit extract^{VII}	1727.35 ± 36.07	1306.66 ± 31.51	NR	1109.19 ± 3.34	NR	NR	NR	
Fruit extract^{VIII}	1798.72 ± 24.56	1263.57 ± 20.49	NR	914.48 ± 17.66	NR	NR	NR	
Fruit extract^{IX}	2208.79 ± 29.54	1441.71 ± 26.74	NR	997.97 ± 9.01	NR	NR	NR	

2,2-diphenyl-1-picrylhydrazyl (DPPH) expressed as TEq μmol/g DE or CS_{50} μg/mL; 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) expressed as TEq μmol/g DE; Ferric Reducing Antioxidant Power (FRAP) expressed as TEq μmol/g DE, μmol Fe (II) Eq/g, or mg GAE/100 g; Oxygen Radical Absorbance Capacity (ORAC) expressed as TEq μmol/g DE or μmol AAE/100 g; Kit Radicaux Libres (KRL) expressed as TEq μmol/g DE; Antioxidant Index 50 (AI_{50}) mg mL^{-1}); Electrochemical Index (EI) μA V^{-1}. Dry Extract (DE); Trolox Equivalent (TEq); Ascorbic Acid Equivalent (AAE); Gallic Acid Equivalent (GAE). 70% acetone extract (E. AC.); Aqueous extract (E. AQ.); 70% methanolic extract (E. M.); Ethanolic extract (E. E.); 50% hydroalcoholic extract (E.H.); Bellavista (I); Hacienda Concepción (II); Jenaro Herrera (III); Contamana (IV); Allpahuayo Mishana (V); San Lorenzo (VI); Atalaya (VII); Palestina (VIII); Tunaants (IX); Not reported (NR)

The antimicrobial mechanism of *O. bataua* likely stems from the antibacterial potential of its phenolic compounds, which primarily destabilize the cytoplasmic membrane. As reported by Zhang et al. (2022), this interaction compromises the integrity and lipid fluidity of the bilayer, resulting in the leakage of intracellular constituents and the dissipation of chemiosmotic potential. Furthermore, specific flavonoid fractions demonstrate selective inhibition of cell wall biosynthesis and the suppression of virulence factors, most notably through the disruption of biofilm formation a critical structure for bacterial pathogenicity and environmental persistence. Consistent with the findings of Dwivedi et al. (2023), the synergistic nature of these metabolites is further evidenced by their capacity to circumvent bacterial resistance mechanisms, acting as adjuvants that restore or amplify the efficacy of conventional antibiotics against multidrug-resistant (MDR) strains.

The authors caution against strictly quantitative interpretations and the premature dismissal of traditional therapies based solely on preliminary in vitro results. They argue that isolated laboratory assays may only capture a fraction of the therapeutic complexity inherent in herbal medicines, thus failing to represent their full synergistic and biological potential. Consequently, the lack of a robust response in simplified experimental models should not invalidate historical ethnobotanical use; rather, it should motivate the adoption of more comprehensive and integrative analytical approaches (Roumy et al. 2015).

While the findings by Roumy et al. (2015) provide compelling evidence of antimicrobial capacity, the clinical application of these extracts against multidrug-resistant (MDR) strains remains in an exploratory stage. Future investigations are essential to isolate the specific chemical classes responsible for overcoming bacterial resistance mechanisms and to elucidate their pharmacodynamics.

Antiproliferative and antienzymatic activity

Research evaluating anti-enzymatic activity has intensified in recent years. A primary focus involves the use of acetylcholinesterase (AChE) inhibitors for the treatment of Alzheimer's disease to enhance cognitive function by preventing the degradation of acetylcholine—a neurotransmitter essential for the central cholinergic system. Among these effective inhibitors, galantamine stands out as a plant-derived compound, which underscores the importance of further investigating natural products for anti-acetylcholinesterase potential (El-Guendouz et al. 2016; Ouknin et al. 2021).

Table 9 Describes the MIC values found for each strain and the species *O. bataua* in the evaluation of antimicrobial activity

Type of sample	Strain	MIC (mg mL^{-1})	References
M.E. fruit	*Stenotrophomonas maltophilia*	2.5	(Roumy et al. 2015)
	Enterococcus faecalis	1.2	
	Enterococcus sp (8152)	1.1	
	Enterococcus sp (8153)	0.6	
	Staphylococcus aureus (8146)	0.6	
	Staphylococcus aureus (8147)	0.6	
	Staphylococcus epidermidis 5001	0.6	
	Staphylococcus epidermidis 10,282	1.1	
	Staphylococcus lugdunensis (T26A3)	0.6	
	Staphylococcus warneri	1.2	
	Corynebacterium striatum (T25-17)	0.2	
	Mycobacterium smegmatis	0.6	
M.E. seed	*Corynebacterium striatum* (T25-17)	2.5	
	Mycobacterium smegmatis	5	

Minimum Inhibitory Concentration (MIC); Melanolic extract (M.E.)

Globally, cancer remains a critical public health challenge (Abdel-Rahman et al. 2021). At the cellular level, cancer encompasses over 150 distinct diseases characterized by dysregulated cell proliferation and the downregulation of pro-apoptotic pathways, making it a leading cause of mortality worldwide (Mohammad et al. 2015). In 2020, approximately 10 million cancer-related deaths were recorded out of 19.3 million new cases diagnosed globally (Radwan et al. 2024).

Despite ongoing global efforts in the fight against cancer, morbidity and mortality rates remain stubbornly high (Sarı et al. 2024). Significant sums are invested annually in disease research and novel treatment development; yet, a decline in cancer incidence has not been achieved (Daimary et al. 2021). A key contributing factor is that many conventional medications induce severe adverse side effects. This toxicity often complicates the treatment of vital organs, such as the heart and liver, which can lead to disease progression (Banik et al. 2022; Daimary et al. 2021). Furthermore, tumor cell resistance to chemotherapy and radiotherapy represents a major obstacle to successful outcomes. Consequently, seeking new therapeutic approaches or chemotherapeutics that minimize side effects, are readily accessible, cost-effective, and more potent against this lethal disease is imperative (Banik et al. 2022).

The species *O. bataua* has demonstrated both antiproliferative and antienzymatic activities (Table 10). Researchers evaluated these properties in *O. bataua* Mart. fruits sourced from nine distinct populations across three genetic groups in the Peruvian Amazon. Antiproliferative activity was assessed using human estrogen-dependent breast cancer (MCF-7), colon cancer (HT-29), and cervical cancer (HeLa) cell lines. The extracts exhibited mild antiproliferative effects specifically against the hormone-dependent MCF-7 lineage. According to the National Cancer Institute (NCI, USA), a crude extract is considered active when the $IC_{50} \leq 20$ µg/mL. However, the samples showed negligible or no cytotoxic/antiproliferative activity against the HT-29 and HeLa cell lines at the concentrations tested (Vargas-Arana et al. 2022).

The exploratory findings of Vargas-Arana et al. (2022) reveal a remarkable cytotoxic selectivity of *O. bataua* extracts, with antiproliferative activity directed almost exclusively toward the MCF-7 cell line. The susceptibility of this hormone-dependent lineage suggests that the mechanism of action arises from refined biochemical modulation rather than non-specific cytotoxicity. This phenomenon may be attributed to flavonoids such as apigenin and luteolin, whose structural conformations confer antiestrogenic properties via competitive binding to estrogen receptors

Table 10 IC_{50} values of antiproliferative and antienzymatic activity found in extracts of *O. bataua* fruits

Sample type	Antiproliferative activity (IC_{50}, μg/mL)			Antienzymatic activity (IC_{50}, μg/mL)		References
	Cell line			Acetylcholinesterase enzymes		
	MCF-7	Ht-29	HeLa	AchE	BchE	
Fruit extract^{I}	443 ± 57	864 ± 121	> 1000	4.52 ± 0.08	7.13 ± 0.10	(Vargas-Arana et al. 2022)
Fruit extract^{II}	270 ± 15	> 1000	> 1000	8.22 ± 0.06	10.40 ± 0.07	
Fruit extract^{III}	484 ± 33	> 1000	> 1000	2.05 ± 0.03	5.95 ± 0.02	
Fruit extract^{IV}	685 ± 88	723 ± 48	> 1000	2.43 ± 0.12	22.38 ± 0.04	
Fruit extract^{V}	366 ± 21	765 ± 65	> 1000	2.91 ± 0.04	7.02 ± 0.01	
Fruit extract^{VI}	255 ± 17	> 1000	> 1000	2.82 ± 0.07	4.78 ± 0.04	
Fruit extract^{VII}	291 ± 25	> 1000	> 1000	8.20 ± 0.15	11.30 ± 0.04	
Fruit extract^{VIII}	747 ± 97	> 1000	> 1000	6.46 ± 0.04	4.42 ± 0.06	
Fruit extract^{IX}	> 1000	> 1000	> 1000	2.52 ± 0.03	4.66 ± 0.06	
Taxol *	13 ± 1	15 ± 2	11 ± 1	NR	NR	
Galantamine *	NR	NR	NR	0.26 ± 0.01	3.82 ± 0.03	

Half-maximal inhibitory concentration (IC_{50}). Values are expressed as mean ± SD (Standard Deviation) from three independent experiments (n = 3). *Positive controls: Taxol (used to evaluate antiproliferative activity) and Galatamine (used to evaluate antienzymatic activity); Bellavista (I); Hacienda Concepción (II); Jenaro Herrera (III); Contamana (IV); Allpahuayo Mishana (V); San Lorenzo (VI); Atalaya (VII); Palestina (VIII); Tunaants (IX); Not reported (NR)

(Collins-Burow et al. 2000). Furthermore, the presence of resveratrol derivatives in "patauá" reinforces its chemopreventive potential. As a polyphenolic phytoalexin, resveratrol operates on multiple fronts: it inhibits inflammatory mediators such as cyclooxygenase and hydroperoxidase, while inducing phase II biotransformation enzymes, thereby promoting cellular detoxification (Jang et al. 1997).

Assessment of the antineoplastic potential of *O. bataua* revealed a selective, concentration-dependent biological response. The discrete antiproliferative activity observed specifically against the MCF-7 cell line suggests an interference mechanism within the estrogen signaling pathway, potentially mediated by flavonoids acting as competitive ligands for estrogen receptors (Collins-Burow et al. 2000). Conversely, the limited cytotoxic activity toward the HT-29 and HeLa lineages corroborates the species' low acute toxicity profile, indicating that its phenolic compounds do not induce non-specific structural damage at standard pharmacological exposure levels (NCI, USA). These findings suggest that, while "patauá" may have a limited scope regarding direct cytotoxicity, its primary relevance may lie in endocrine modulation and genomic protection against pre-neoplastic oxidative damage, rather than robust tumoricidal action.

The convergence of these properties with antienzymatic activities (AChE and BChE) suggests a pleiotropic effect of the fruit's phytochemical constituents. Furthermore, the low responsiveness of HT-29 and HeLa lineages to the concentrations tested corroborates the established history of "patauá" as a safe dietary staple among Amazonian populations. The absence of acute toxicity in non-estrogen-dependent cells indicates that the species bioactive compounds function primarily as genomic protective agents and metabolic regulators rather than aggressive tumoricidal substances. These findings validate its profile as a safe and promising functional food (Vargas-Arana et al. 2022).

The anti-enzymatic potential of *O. bataua* was evaluated through the inhibition of acetylcholinesterase (AChE) and butyrylcholinesterase (BChE). Several phenolic compounds identified in the extract demonstrated significant inhibitory activity against these enzymes (Table 10) (Vargas-Arana et al. 2022). These robust findings suggest that *O. bataua* secondary metabolites function as effective enzyme inhibitors. As discussed by Vargas-Arana et al. (2022), this property is attributed to the structural affinity of specific phenolics for the enzymes catalytic and peripheral anionic sites. The probable mechanism

involves hydrophobic interactions and hydrogen bonding that stabilize the enzyme-inhibitor complex, thereby impeding acetylcholine hydrolysis. This capacity for enzymatic modulation, combined with the species antioxidant potential, positions "patauá" as a promising source of neuroprotective molecules for the management of cognitive disorders associated with oxidative stress and cholinergic dysfunction (Larrazábal-Fuentes et al. 2020).

The inhibition of cholinesterases by *O. bataua* constituents is further supported by the presence of high-polarity phenolic metabolites, which exhibit strong thermodynamic affinity for the catalytic domains of AChE and BChE. The efficacy of this interaction is exemplified by isoastilbin, a common South American flavonoid, whose inhibitory capacity ($\sim$ 50% at concentrations as low as 2.2 μM) demonstrates efficient anchoring within the enzymatic active sites (Barrientos et al. 2020). This bioactivity is corroborated by molecular docking studies indicating favorable binding energies for compounds such as glycosylated apigenin and kaempferol. As reported by Larrazábal-Fuentes et al. (2020), the low binding free energy values observed for acetylcholinesterase (TcAChE) and butyrylcholinesterase (hBChE) suggest that these polyphenols stably occupy the catalytic gorge, thereby obstructing substrate access. Consequently, these flavonoid classes in "patauá" not only provide antioxidant benefits but also establish a mechanistic foundation for its role as a neuroprotective agent through cholinergic modulation.

Antimalarial activity

Malaria remains a leading cause of mortality and morbidity globaly (Savi 2022). It is a parasitic disease caused by protozoans of the genus *Plasmodium* and transmitted to humans by the bite of infected female Anopheles mosquitoes. While over 200 *Plasmodium* species affect various mammals, birds, and reptiles, they are generally highly species-specific. The primary species infecting humans include *P. falciparum*, *P. vivax*, *P. ovale*, and *P. malariae*. More recently, zoonotic infections by *P. knowlesi* and other non-human primate plasmodia have been documented in human populations (Gozalo et al. 2024). According to the World Health Organization (WHO), malaria claims approximately half a million lives annually (Garrido-Cardenas et al. 2019). *Plasmodium falciparum* infections range from asymptomatic cases and uncomplicated febrile illness to severe conditions characterized by coma, acidosis, or severe anemia. To enhance efficacy and mitigate the development of drug resistance, artemisinin-based combination therapy (ACT) is currently the globally recommended treatment. The clinical manifestation of severe malaria varies based on age and immune status, necessitating a range of supportive measures alongside effective antimalarial intervention (Bell and Molyneux 2007).

Although several antimalarial drugs have been developed from plants or their semi-synthetic analogues, the alarming rise in drug resistance across most therapeutic classes, coupled with persistent endemicity, remains a critical public health challenge (Siqueira-Neto et al. 2023). While plants have historically served as excellent reservoirs for antimalarial compounds sometimes outperforming existing drugs there is still an urgent need for novel, safe, effective, and affordable treatments. A recent study evaluated the efficacy of "patauá" pulp extract against *Plasmodium falciparum* following simulated human digestion (Lima et al. 2025). The results demonstrated that both undigested and digested extracts exhibited antiplasmodial activity; however, the digested extract proved more promising due to its superior potency and selectivity, characterized by a lower IC_{50} and a higher selectivity index (Table 11). This enhancement in antimalarial performance following simulated digestion suggests that the gastrointestinal process facilitates the activation or release of secondary metabolites. The increased bioaccessibility of compounds such as catechin and vanillic acid (Rezaire et al. 2014; Saravia et al. 2020) indicates that enzymatic hydrolysis and pH transitions may liberate these molecules from the fruit matrix, thereby enhancing their systemic bioactivity.

The underlying biological mechanism involves the capacity of these phenolic compounds to mitigate the oxidative stress exacerbated by infection, potentially disrupting the parasite's redox homeostasis. As noted by Finco et al. (2012), the significance of these bioactives is underscored by their selective cytotoxicity; they act deleteriously against *Plasmodium* while preserving the integrity of human host cells. Consequently, these findings indicate that digestion not only maintains but may also enhance the therapeutic potential of *O. bataua*, converting stable precursors into bioavailable agents with a substantial

Table 11 IC_{50} values of antimalarial activity found in extracts of *O. bataua* fruits

Sample type	Strains	IC_{50} (μg/mL)	SI	References
H.E. pulp undigested	*P. falciparum*	6265	1.28 (HCT-8)	(Lima et al. 2025)
			1.20 (A549)	
			1.12 (HUVEC)	
H.E. pulp digested		2024	3.92 (HCT-8)	
			3.68 (A549)	
			3.43 (HUVEC)	

Half-maximal inhibitory concentration (IC_{50}); Selectivity index (SI). Values are expressed in μg/mL where applicable. 50% hydroalcoholic extract (H.E.)

pharmacological safety margin (Lima et al. 2025). Nevertheless, the current data remain exploratory, necessitating in vivo studies to validate these antiplasmodial effects.

The researchers suggest that "patauá" pulp extract holds significant promise as an antimalarial agent, while emphasizing the necessity of critically evaluating data derived solely from raw samples particularly when such materials are intended for food, pharmaceutical, or nutraceutical development. Nevertheless, several challenges persist, especially concerning the bioavailability of polyphenol-rich extracts and their clinical translation. By identifying novel, value-added applications for Amazonian fruits, we can foster the conservation of regional biodiversity while uncovering potent new ingredients for global industries (Lima et al. 2025).

Conclusion

One of the primary challenges of this research was the paucity of data regarding the chemical composition and biological activities of *O. bataua* oil, particularly concerning samples from the Brazilian Amazon. Despite this scarcity, *O. bataua* demonstrates significant potential for developing novel products derived from its botanical components.

The oil extracted from this species holds great promise for the cosmetic and pharmaceutical industries, specifically in the formulation of innovative delivery systems. These include emulgels, organogels, nanoemulgels, conventional and Pickering emulsions, nanoemulsions, lipid nanoparticles, nanocapsules, and microcapsules.

Furthermore, extracts obtained from various plant parts rich in antioxidant compounds and possessing diverse biological activities are suitable for both innovative and conventional food, cosmetic, and pharmaceutical applications. Potential products encompass hydrogels, polymeric gels, polymeric nanoparticles, microparticles, nutraceutical gummies, and cosmetic formulations such as anti-aging facial creams.

In this context, future research should prioritize the in-depth investigation of specific plant derivatives, their technological applications, and the execution of clinical trials to validate their safety and efficacy.

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Declarations

Conflict of interest The authors declare no competing interests.

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