Plant-Derived Hydrolates as Functional Components in Nanostructured Topical Systems: A Comparative Study of Hydrolate-Based Nanogel and Emulgel Platforms

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Abstract

Plant-derived hydrolates are aqueous co-products of hydrodistillation that remain underexplored despite their potential as sustainable bioactive ingredients. This study comparatively evaluated two nanostructured topical platforms for hydrolate valorization: a thermoresponsive nanogel containing *Anacardium occidentale* L. hydrolate and a nanostructured emulgel containing *Pectis brevipedunculata* hydrolate associated with babassu oil. Both systems were based on Pluronic F127 and Carbopol 974P and were characterized by physical stability assessment, Fourier transform infrared spectroscopy, differential scanning calorimetry, scanning electron microscopy, and antimicrobial assays against *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans*.

Hydrolate incorporation influenced the supramolecular organization and biological performance of both platforms, although in a formulation-dependent manner. The *A. occidentale* hydrolate-loaded nanogel showed thermoresponsive behavior, hydrolate–polymer interactions, reduced crystallinity, compact lamellar morphology, and antimicrobial activity at the highest tested concentration. The *P. brevipedunculata* hydrolate-loaded emulgel preserved the structural integrity of the matrix, enhanced hydrogen bonding interactions, displayed a porous amorphous morphology, and improved antifungal performance at lower concentration. Overall, these findings indicate that plant-derived hydrolates can act as functional components rather than inert aqueous residues, supporting their use in sustainable nanostructured topical systems with antimicrobial potential.

Keywords: hydrolates; nanogel; emulgel; *Anacardium occidentale*; *Pectis brevipedunculata*; Pluronic F127; Carbopol 974P; antimicrobial activity; topical formulation; circular economy.

Introduction

The growing demand for sustainable, biocompatible, and multifunctional topical systems has stimulated increasing interest in plant-derived materials, particularly those obtained from medicinal and aromatic species. Natural products remain important sources of bioactive compounds for pharmaceutical, cosmetic, and biomedical applications because of their chemical diversity and broad spectrum of biological properties, including antimicrobial, antioxidant, and anti-inflammatory effects.[1,2] In parallel, the development of topical delivery platforms has advanced toward systems capable of improving the stability, retention, and local performance of natural bioactives, especially in applications associated with microbial control and skin-related care.[3,4]

Among plant-derived materials, hydrolates represent aqueous co-products generated during hydrodistillation, together with essential oils. Although essential oils have been extensively investigated due to their high content of volatile terpenoids and other lipophilic constituents, hydrolates have historically received less attention and are frequently considered low-value fractions or secondary residues of the extraction process.[5,6] However, these aqueous fractions may contain water-soluble volatile compounds, oxygenated terpenes, phenolic derivatives, and other polar constituents capable of contributing to biological activity. Their lower concentration of lipophilic compounds, aqueous nature, and potential compatibility with hydrophilic matrices make hydrolates particularly attractive for the development of safer and more sustainable topical formulations.[6,7]

The valorization of hydrolates is also aligned with the principles of green chemistry and circular economy, since it promotes the fuller use of plant biomass and reduces waste generated during essential oil production.[8–10] This approach is especially relevant in biodiversity-rich regions, where aromatic and medicinal plants can support the development of value-added bioproducts while contributing to local bioeconomy strategies. In this context, the transformation of hydrolates from underutilized co-products into functional formulation components represents an opportunity to integrate sustainability, technological innovation, and

biological performance in a single platform.[5,11]

Nanostructured topical systems offer important advantages for the incorporation of plant-derived components, including improved physicochemical stability, enhanced interaction with biological surfaces, and modulation of the release and local availability of active constituents.[12–14] Among these systems, thermoresponsive nanogels and emulgels based on Pluronic F127 and Carbopol 974P are particularly attractive. Pluronic F127 is a poly(ethylene oxide)–poly(propylene oxide)–poly(ethylene oxide) triblock copolymer capable of forming micellar structures and undergoing temperature-dependent sol–gel transitions, whereas Carbopol 974P contributes to matrix structuring, viscosity modulation, and topical retention.[15–17] The combination of these polymers provides a versatile framework for designing hydrophilic and biphasic topical platforms containing plant-derived hydrolates.

Despite the growing interest in hydrolates and nanostructured formulations, comparative studies addressing how different hydrolate-containing topical architectures influence physicochemical organization and antimicrobial performance remain limited. Most available studies evaluate individual plant species or isolated formulation systems, which restricts the understanding of hydrolates as functional components across different matrix designs. A comparative perspective is therefore useful to determine whether hydrolates act only as aqueous vehicles or whether they can actively modulate supramolecular organization, thermal behavior, morphology, and biological response in nanostructured topical systems.

In this study, two hydrolate-based nanostructured topical platforms were comparatively evaluated: a thermoresponsive nanogel containing *Anacardium occidentale* L. hydrolate and a nanostructured emulgel containing *Pectis brevipedunculata* hydrolate associated with babassu oil. These systems were selected as complementary formulation architectures because they represent distinct strategies for hydrolate valorization: a hydrophilic polymeric nanogel and a biphasic emulgel containing both aqueous hydrolate and lipid components. The platforms were compared in terms of physical stability, Fourier transform infrared spectroscopy, differential scanning calorimetry, scanning electron microscopy, and antimicrobial

activity against *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans*.

The central hypothesis of this work is that plant-derived hydrolates should not be regarded merely as residual aqueous fractions, but rather as functional components capable of influencing the organization and performance of nanostructured topical systems. By comparing hydrolate-based nanogel and emulgel platforms, this study aims to provide a broader understanding of how formulation architecture modulates the contribution of hydrolates to physicochemical properties and antimicrobial activity, supporting their use as sustainable bioactive ingredients in topical formulation science.

Materials and Methods

This study was designed as a comparative evaluation of two hydrolate-based nanostructured topical platforms developed using related polymeric matrices but distinct formulation architectures. The first platform consisted of a hydrophilic thermoresponsive nanogel containing *Anacardium occidentale* L. hydrolate, whereas the second consisted of a biphasic emulgel containing *Pectis brevipedunculata* hydrolate associated with babassu oil. The methodological organization was structured to enable comparison across common analytical endpoints, including physical stability, spectroscopic interactions, thermal behavior, morphology, and antimicrobial performance.

Materials

Pluronic F127, a poly(ethylene oxide)–poly(propylene oxide)–poly(ethylene oxide) triblock copolymer, ultrapure water, and analytical-grade reagents were obtained from Merck (Rahway, NJ, USA). Carbopol 974P NF was supplied by IMCD Brazil (São Paulo, Brazil). Babassu fixed oil, obtained from *Attalea speciosa*, was kindly provided by the Cooperative of Small Agroextractivist Producers of Lago do Junco (COPPALJ), Maranhão, Brazil. Mueller–Hinton broth (MHB), Potato Dextrose Broth (PDB), resazurin, gentamicin, ampho-

tericin B, and all microbiological media and reagents were of analytical or microbiological grade. All materials were used as received without further purification.

Plant Material and Hydrolate Obtention

Leaves of *Anacardium occidentale* L. were collected on the campus of the Federal University of Maranhão (UFMA), São Luís, MA, Brazil (2°33'13.9" S; 44°18'22.0" W). The plant material was shade-dried at room temperature for 15 days to reduce residual moisture and preserve volatile constituents. After drying, 300 g of leaves were fragmented and subjected to hydrodistillation using a Clevenger-type apparatus with 600 mL of distilled water. The extraction was carried out for 2.5 h under continuous distillation. The aqueous fraction obtained after condensation was separated and stored under refrigeration until use as *A. occidentale* hydrolate.

Pectis brevipedunculata (Gardner) Sch.Bip. was collected on the campus of UFMA, São Luís, MA, Brazil (2°33'20.5" S; 44°18'32.7" W). A voucher specimen was deposited in the Herbarium Rosa Mochel (SLUI), Universidade Estadual do Maranhão, São Luís, MA, Brazil, under voucher number 5287. Plant collection was registered in the Brazilian National System for Genetic Heritage and Associated Traditional Knowledge (SisGen; registration no. AAFB38B). The plant material was shade-dried at 25 °C for 48 h, fragmented to approximately 1–2 cm, and subjected to hydrodistillation using a Clevenger-type apparatus. Briefly, 300 g of plant material were distilled with 500 mL of distilled water for 2.5 h after the onset of reflux. After cooling to room temperature, the hydrolate was separated from the essential oil phase using a separatory funnel, filtered through Whatman No. 1 filter paper and, when necessary, further clarified using membrane filtration or centrifugation. The purified hydrolate was stored in amber glass bottles under refrigeration until use.

Babassu Oil Characterization

The babassu oil used in the emulgel platform was characterized to support its use as the lipid phase of the formulation. The acidity of the oil was determined according to the official method of the American Oil Chemists' Society (AOCS Cd 3d-63). Briefly, approximately 2 g of oil were dissolved in an ethanol and diethyl ether mixture, using phenolphthalein as an indicator, and titrated with standardized sodium hydroxide solution until a persistent pale pink endpoint was observed. The acidity percentage was calculated according to Equation 1.

$$Acidity\ (\%) = \frac{V \times N \times F \times 100}{m} \tag{1}$$

where V is the volume of sodium hydroxide solution used in the titration (mL), N is the normality of the sodium hydroxide solution, F is the conversion factor corresponding to the selected reference fatty acid, and m is the mass of the oil sample (g). The iodine value and saponification value were determined according to AOCS methods Cd 1c-85 and Cd 3-94, respectively.

The fatty acid composition of babassu oil was determined after conversion to fatty acid methyl esters (FAMEs). The methyl esters were analyzed by gas chromatography equipped with a flame ionization detector and a capillary column suitable for fatty acid separation. Helium was used as the carrier gas, and individual fatty acids were identified by comparison of retention times with those of authentic standards analyzed under the same conditions. Results were expressed as relative percentages of total fatty acids.

Preparation of the *Anacardium occidentale* Hydrolate-Based Nanogel Platform

The *A. occidentale* hydrolate-loaded nanogel platform was prepared using the cold method. Different proportions of hydrolate and water were evaluated in the aqueous phase, while the concentrations of Pluronic F127 and Carbopol 974P were kept constant at 20% and 0.2%,

respectively. Pluronic F127 was gradually dispersed into the cold aqueous phase under magnetic stirring in an ice bath at 5–10 °C until complete solubilization. Subsequently, Carbopol 974P was incorporated under continuous stirring. The resulting dispersions were homogenized using an ultrasonic bath for 10 min to improve system uniformity and minimize aggregate formation. The formulations were stored under refrigeration until further analyses.

Four nanogel formulations were prepared containing 25, 50, 75, and 100% hydrolate in the aqueous phase, designated nG25, nG50, nG75, and nG100, respectively. After physical stability assessment, the formulation containing 100% hydrolate in the aqueous phase was selected for further characterization and designated Ao-NG. This formulation represented the hydrolate-based nanogel platform used in the comparative analysis.

Preparation of the *Pectis brevipedunculata* Hydrolate-Based Emulgel Platform

The *P. brevipedunculata* hydrolate-loaded emulgel platform was prepared using a cold emulsification approach. Pluronic F127 was gradually dispersed in the cold aqueous phase under continuous stirring in an ice bath at 5–10 °C until complete hydration of the polymer chains. Carbopol 974P was then incorporated under continuous stirring until a homogeneous polymeric matrix was obtained. Babassu oil was added dropwise under stirring, and the mixture was subjected to ultrasonic treatment for 7–10 min to promote oil dispersion and formation of a nanostructured emulgel system.

Hydrolate-loaded emulgel formulations were prepared by replacing part of the aqueous phase with *P. brevipedunculata* hydrolate. In the final optimized emulgel platform, Pluronic F127, Carbopol 974P, and babassu oil were maintained at 20%, 0.1%, and 3%, respectively, while the hydrolate was incorporated into the aqueous phase. The optimized hydrolate-containing emulgel was designated Pb-EG and was compared with the corresponding emulgel without hydrolate, designated EG. This comparison enabled the evaluation of the contribution of the hydrolate to the physicochemical organization and antimicrobial performance of

the emulgel platform.

Formulation Design and Comparative Organization

The formulation design was organized to preserve the specificity of each platform while enabling comparison across common analytical endpoints. The *A. occidentale* system was developed as a hydrophilic thermoresponsive nanogel, whereas the *P. brevipedunculata* system was developed as a biphasic emulgel containing babassu oil as lipid phase. Therefore, the comparison was based on the functional role of hydrolate incorporation within each formulation architecture rather than on direct equivalence between the two plant species.

Table 1: Comparative overview of the hydrolate-based nanostructured topical platforms evaluated in this study.

Ao-NG: *Anacardium occidentale* hydrolate-based nanogel	
Platform type	Hydrolate-based nanogel
Hydrolate source	*Anacardium occidentale* L.
Matrix composition	Pluronic F127 and Carbopol 974P
Formulation architecture	Hydrophilic thermoresponsive polymeric platform
Role in the comparative study	Model system for evaluating hydrolate incorporation into a hydrophilic nanogel matrix
Pb-EG: *Pectis brevipedunculata* hydrolate-based emulgel	
Platform type	Hydrolate-based emulgel
Hydrolate source	*Pectis brevipedunculata* (Gardner) Sch.Bip.
Matrix composition	Pluronic F127, Carbopol 974P, and babassu oil
Formulation architecture	Biphasic nanostructured polymer–lipid platform
Role in the comparative study	Model system for evaluating hydrolate incorporation into an emulgel containing a lipid phase

Physical Stability Assessment

The physical stability of the formulations was evaluated by macroscopic inspection and accelerated thermal cycling. Samples were monitored for homogeneity, phase separation, sedimentation, color, odor, and general appearance. Thermal cycling was performed according to adapted cosmetic stability guidelines, consisting of seven consecutive cycles of 24

h at 5 °C followed by 24 h at room temperature. The formulations were also monitored during refrigerated storage to evaluate the maintenance of their physical characteristics over time.[18,19]

For the nanogel platform, formulations containing different proportions of *A. occidentale* hydrolate were compared to identify the system with the most suitable macroscopic stability and thermoresponsive behavior. For the emulgel platform, the hydrolate-containing formulation was compared with the corresponding hydrolate-free emulgel to evaluate the influence of *P. brevipedunculata* hydrolate on the stability and physical organization of the biphasic system.

Fourier Transform Infrared Spectroscopy

Fourier transform infrared spectroscopy (FTIR) was performed to identify functional groups and investigate possible interactions between hydrolate constituents and the polymeric matrices. Samples were previously lyophilized to remove residual moisture, mixed with potassium bromide, and compressed into pellets. Spectra were recorded using a Shimadzu Tracer-100 spectrophotometer in the mid-infrared region from 4000 to 400 cm^{-1}.

The spectra of hydrolate-containing formulations were compared with those of the corresponding blank or reference systems. For Ao-NG, the hydrolate-loaded nanogel was compared with the polymeric nanogel matrix without hydrolate. For Pb-EG, the hydrolate-loaded emulgel was compared with the hydrolate-free emulgel and, when appropriate, with the individual formulation components. Spectral changes in the O–H stretching region, C–H stretching region, carbonyl region, and C–O–C stretching region were used to evaluate hydrogen bonding, preservation of matrix components, and possible hydrolate–polymer interactions.

Differential Scanning Calorimetry

Differential scanning calorimetry (DSC) was used to evaluate the thermal behavior of the formulations and possible changes in matrix organization after hydrolate incorporation. Samples were placed in aluminum pans and analyzed using a DSC-60H calorimeter (Shimadzu, Kyoto, Japan) under a nitrogen atmosphere with a flow rate of 100 mL min^{-1}. The thermal events of the hydrolate-containing systems were compared with those of the corresponding reference formulations to assess changes in crystallinity, thermal transitions, and structural organization.

For the Ao-NG platform, DSC analysis was performed to evaluate changes associated with the incorporation of *A. occidentale* hydrolate into the Pluronic F127/Carbopol matrix. For the Pb-EG platform, DSC was used to compare the emulgel without hydrolate and the hydrolate-loaded emulgel, with emphasis on the preservation of thermoresponsive behavior, changes in heat flow profile, and possible modification of matrix homogeneity.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) was used to investigate the morphology of the nanostructured topical platforms. Samples were previously frozen and lyophilized to preserve the structural organization of the matrices. The dried samples were mounted on appropriate supports and analyzed by scanning electron microscopy at different magnifications.

The morphology of Ao-NG and Pb-EG was comparatively evaluated to identify structural features associated with each formulation architecture. The nanogel platform was assessed for compactness, lamellar organization, and porosity, whereas the emulgel platform was assessed for surface continuity, pore formation, matrix heterogeneity, and integration between the polymeric and lipid phases. The morphological observations were interpreted together with FTIR and DSC results to support the discussion of hydrolate-induced structural organization.

Antimicrobial Activity

The antimicrobial activity of the formulations was evaluated against *Escherichia coli* ATCC 25922, *Staphylococcus aureus* ATCC 25923, and *Candida albicans* ATCC 443-805-2. Bacterial strains were obtained from the Food and Water Quality Control Microbiology Laboratory of the Federal University of Maranhão, while the fungal strain was provided by the Immunology and Mycology Laboratory. Access to genetic resources was registered in the Brazilian National System for Genetic Heritage and Associated Traditional Knowledge (SisGen; registration no. A3FAD1C).

Bacterial strains were cultured in MHB, whereas *C. albicans* was cultured in PDB. Microbial suspensions were adjusted according to the 0.5 McFarland standard, corresponding to approximately 1.5×10^8 CFU/mL for bacteria and 1.5×10^6 CFU/mL for *C. albicans*, following adapted Clinical and Laboratory Standards Institute recommendations.[20–22]

The formulations were evaluated at 100% and 50% concentrations using the broth microdilution method in sterile 96-well microplates. In each well, 100 μL of formulation were mixed with 100 μL of standardized microbial suspension. Growth control, sterility control, and vehicle control were included in all assays. Gentamicin and amphotericin B were used as positive controls for antibacterial and antifungal assays, respectively. After incubation at 37 °C for 24 h for bacterial strains and 35 °C for 48 h for *C. albicans*, 20 μL of resazurin solution (0.01%, w/v) was added to each well, followed by an additional incubation period of 2–4 h under the same conditions. Maintenance of the blue color indicated inhibition of microbial metabolic activity, whereas a color change to pink indicated microbial growth.

Due to the semisolid nature and viscosity of the nanogel and emulgel formulations, the antimicrobial assay was performed using fixed concentrations rather than conventional serial dilutions. Therefore, the results were interpreted as indicative inhibitory responses under the experimental conditions rather than conventional minimum inhibitory concentration values derived from full dilution series. This approach allowed comparative assessment of antimicrobial performance among the hydrolate-containing systems and their corresponding controls.

Statistical Analysis

All experiments were performed in triplicate, and the results were expressed as mean values or qualitative responses according to the nature of each assay. When applicable, statistical analysis was performed using one-way analysis of variance followed by Tukey's post hoc test, adopting a significance level of $p < 0.05$. For antimicrobial assays based on resazurin response, results were expressed using the same semiquantitative 0–3 resazurin-based metabolic activity scale adopted in the Results section, enabling comparison between formulations, concentrations, and controls.

Comparative Data Analysis

The two hydrolate-based platforms were compared qualitatively and semi-quantitatively based on formulation architecture, physical stability, FTIR spectral changes, DSC thermal behavior, SEM morphology, and antimicrobial performance. Because the nanogel and emulgel systems represent distinct formulation architectures, the comparative analysis was not intended to establish direct equivalence between *A. occidentale* and *P. brevipeduncu-lata* hydrolates. Instead, the analysis focused on identifying how hydrolate incorporation contributed to the organization and functional performance of each nanostructured topical platform. This approach allowed the role of plant-derived hydrolates to be discussed beyond their conventional interpretation as residual aqueous fractions, highlighting their potential as functional components in sustainable topical formulation design.

Results and Discussion

Fatty Acid Composition and Physicochemical Properties of Babassu Oil

The fatty acid composition and physicochemical properties of babassu oil were evaluated to support its role as the lipid phase of the Pb-EG platform. This characterization is relevant because, unlike Ao-NG, which is a hydrophilic polymeric nanogel, Pb-EG contains a polymer–lipid architecture in which babassu oil contributes to the structural organization and potential biological performance of the emulgel matrix.

Babassu oil was predominantly composed of saturated fatty acids, which accounted for 86.01% of the total fatty acid content. Lauric acid was the major constituent, representing 45.66 g/100 g of total fatty acids, followed by myristic acid, oleic acid, palmitic acid, caprylic acid, and capric acid. The high proportion of medium-chain saturated fatty acids is consistent with the typical composition of lauric oils and supports the oxidative stability of the lipid phase. In addition, lauric, caprylic, and capric acids have been associated with membrane-disruptive effects, which may contribute to the antimicrobial performance observed for the emulgel system.[23–26]

The monounsaturated fatty acid fraction was mainly represented by oleic acid, corresponding to 11.98% of the total composition. Oleic acid is commonly associated with modulation of lipid packing and may contribute to the interaction of topical formulations with biological membranes. In contrast, polyunsaturated fatty acids were present at low levels, mainly as linoleic acid, which further supports the oxidative stability of the oil. The iodine value of 13.73 g I_2/100 g confirmed the low degree of unsaturation, whereas the saponification value of 244.04 mg KOH/g indicated the predominance of short- and medium-chain fatty acids.[24,27,28]

Overall, the physicochemical profile of babassu oil supports its selection as a multifunctional lipid component in the Pb-EG platform. Its high content of saturated medium-chain

fatty acids may contribute not only to the physical stability of the emulgel matrix, but also to its antimicrobial potential. Therefore, the presence of babassu oil should be considered an important formulation variable when interpreting the comparative performance of Pb-EG in relation to the hydrophilic Ao-NG system.

Table 2: Fatty acid composition and physicochemical parameters of babassu oil (COPPALJ, Maranhão, Brazil).

Parameter	**Value**
Fatty acid composition (g/100 g)	
Caprylic acid (C8:0)	7.62
Capric acid (C10:0)	6.38
Lauric acid (C12:0)	45.66
Tridecanoic acid (C13:0)	0.07
Myristic acid (C14:0)	14.92
Pentadecylic acid (C15:0)	0.03
Palmitic acid (C16:0)	8.09
Margaric acid (C17:0)	0.05
Stearic acid (C18:0)	3.28
Oleic acid (C18:1, ω-9)	11.98
Linoleic acid (C18:2, ω-6)	1.86
Linolenic acid (C18:3, ω-3)	0.08
Fatty acid classes (%)	
Saturated fatty acids (SFA)	86.01
Monounsaturated fatty acids (MUFA)	11.98
Polyunsaturated fatty acids (PUFA)	1.94
Physicochemical parameters	
Iodine value	13.73 g I_2/100 g
Saponification value	244.04 mg KOH/g

Formulation Development and Physical Stability

The formulation design adopted in this study enabled the evaluation of two complementary strategies for incorporating plant-derived hydrolates into nanostructured topical systems. Ao-NG was developed as a hydrophilic thermoresponsive nanogel in which *A. occidentale* hydrolate constituted the aqueous phase of a Pluronic F127/Carbopol 974P matrix. In contrast, Pb-EG was developed as a biphasic emulgel in which *P. brevipedunculata* hydrolate was incorporated into the aqueous phase of a Pluronic F127/Carbopol 974P system contain-

ing babassu oil as lipid component. This organization allowed the comparative assessment of hydrolate incorporation in polymeric and polymer–lipid formulation architectures.[3,16,17]

A simplified formulation code system was adopted to ensure consistency throughout the manuscript and to facilitate comparative interpretation. Candidate nanogel formulations were coded sequentially as NG-1 to NG-9, whereas candidate emulgel formulations were coded as EG-1 to EG-19. The abbreviation HDAo was used for *Anacardium occidentale* hydrolate, and HDPb was used for *Pectis brevipedunculata* hydrolate. After formulation screening, NG-9 was selected as the representative HDAo-loaded nanogel and is hereafter referred to as Ao-NG, whereas EG-19 was selected as the representative HDPb-loaded emulgel and is hereafter referred to as Pb-EG. The formulation codes, compositions, stability responses, and selection criteria are summarized in Table 3.

The development of the Ao-NG platform was initially guided by the optimization of the thermoresponsive polymeric matrix before hydrolate incorporation. Combinations containing 5–10% Pluronic F127 and 0.1–0.3% Carbopol 974P remained liquid at both 5 and 30 °C, indicating the absence of thermoresponsive behavior. In contrast, formulations containing 20% Pluronic F127 and 0.1–0.3% Carbopol 974P remained liquid at 5 °C and transitioned to a semi-solid state at 30 °C, with an approximate sol–gel transition time of 10 min. Among these systems, the formulation containing 20% Pluronic F127 and 0.1% Carbopol 974P showed low viscosity, whereas the formulation containing 20% Pluronic F127 and 0.3% Carbopol 974P showed excessive viscosity. Therefore, the 20:0.2 F127:974P combination was selected as the optimized blank matrix for HDAo incorporation.[15,29,30]

Based on this optimized matrix, HDAo was incorporated at 25%, 50%, 75%, and 100% of the aqueous phase. All hydrolate-loaded nanogel formulations showed homogeneous macroscopic appearance and stability under the evaluated conditions. The formulation containing 100% HDAo in the aqueous phase was selected because it preserved the thermoresponsive behavior of the matrix while maximizing hydrolate incorporation. This formulation was designated Ao-NG and used as the representative hydrolate-based nanogel platform in sub-

sequent analyses.[17,31]

For the Pb-EG platform, formulation development was based on the optimization of a biphasic emulgel containing Pluronic F127, Carbopol 974P, and babassu oil. Base formulations were first prepared without hydrolate to identify the most suitable balance between polymer concentration, lipid content, physical form, and stability. Formulations with lower Pluronic F127 concentrations resulted in liquid or liquid-gel systems, whereas formulations containing 20% Pluronic F127 showed emulgel characteristics. Among the base systems, the formulation containing 20% Pluronic F127, 0.1% Carbopol 974P, and 3% babassu oil exhibited suitable stability and was selected as the reference emulgel matrix for HDPb incorporation.[3,12,32]

HDPb-loaded emulgel formulations were then prepared by replacing part of the aqueous phase with increasing proportions of HDPb, while maintaining the total aqueous phase at 76.9% of the formulation and fixing the concentrations of Pluronic F127, Carbopol 974P, and babassu oil at 20%, 0.1%, and 3%, respectively. Hydrolate proportions ranging from 10% to 50% of the aqueous phase were evaluated. All HDPb-loaded emulgels remained stable under the tested conditions, indicating that the optimized polymer–lipid matrix was able to accommodate increasing amounts of hydrolate without macroscopic destabilization. The formulation containing 50% HDPb in the aqueous phase was selected as Pb-EG because it represented the highest hydrolate-loaded system while preserving physical stability.[3,31,33]

From a comparative perspective, the physical stability results support the feasibility of using plant-derived hydrolates as functional formulation components in different nanostructured topical platforms. Ao-NG demonstrates that HDAo can replace the aqueous phase of a thermoresponsive nanogel while preserving macroscopic stability and gelation behavior. Pb-EG demonstrates that HDPb incorporation can also be combined with a lipid phase to produce a stable emulgel system. These findings reinforce the potential of hydrolates as value-added co-products for sustainable topical formulation design.[5,6,8,9]

Table 3: Simplified codes and composition of candidate formulations used to develop the Ao-NG and Pb-EG platforms.

Code	Water	HDAo	HDPb	F127	974P	OAs	Stability	Selection
Nanogel matrix screening								
NG-1	q.s.	–	–	5	0.1–0.3	–	NT	–
NG-2	q.s.	–	–	10	0.1–0.3	–	NT	–
NG-3	q.s.	–	–	20	0.1	–	T, LV	–
NG-4	q.s.	–	–	20	0.2	–	T, SV	Matrix selected
NG-5	q.s.	–	–	20	0.3	–	T, HV	–
Hydrolate-loaded nanogel formulations								
NG-6	75	25	–	20	0.2	–	S	–
NG-7	50	50	–	20	0.2	–	S	–
NG-8	25	75	–	20	0.2	–	S	–
NG-9	–	100	–	20	0.2	–	S	Selected as Ao-NG
Base emulgel formulations without hydrolate								
EG-1	84.8	–	–	10	0.2	5	–	–
EG-2	79.8	–	–	10	0.2	10	–	–
EG-3	74.8	–	–	10	0.2	15	–	–
EG-4	79.8	–	–	15	0.2	5	–	–
EG-5	74.8	–	–	15	0.2	10	–	–
EG-6	69.8	–	–	15	0.2	15	–	–
EG-7	74.8	–	–	20	0.2	5	C	–
EG-8	69.8	–	–	20	0.2	10	C	–
EG-9	64.8	–	–	20	0.2	15	PS	–
EG-10	78.9	–	–	20	0.1	1	–	–
EG-11	77.9	–	–	20	0.1	2	S	–
EG-12	76.9	–	–	20	0.1	3	S	Reference EG
EG-13	75.9	–	–	20	0.1	4	S	–
EG-14	74.9	–	–	20	0.1	5	PS	–
Hydrolate-loaded emulgel formulations								
EG-15	90	–	10	20	0.1	3	S	–
EG-16	80	–	20	20	0.1	3	S	–
EG-17	70	–	30	20	0.1	3	S	–
EG-18	60	–	40	20	0.1	3	S	–
EG-19	50	–	50	20	0.1	3	S	Selected as Pb-EG

Values are expressed as percentage (w/w), except for the nanogel matrix screening, in which water was added quantum satis (q.s.) to complete the formulation. For NG-6 to NG-9, Water and HDAo values refer to the aqueous phase ratio. For EG-15 to EG-19, Water and HDPb values refer to the aqueous phase ratio, while the total aqueous phase was maintained at 76.9% of the formulation. HDAo: *Anacardium occidentale* hydrolate. HDPb: *Pectis brevipedunculata* hydrolate. OAs: oily actives, corresponding to babassu oil. NT: no thermoresponsive behavior; T: thermoresponsive; LV: low viscosity; SV: suitable viscosity; HV: high viscosity; S: stable; C: creaming; PS: phase separation.

The macroscopic appearance of the final selected formulations and the thermoresponsive behavior of Ao-NG are shown in Figures S1–S3. This supplementary figure visually supports the formulation screening results by showing the final HDAo-loaded nanogel selected as Ao-NG, its sol–gel transition behavior, and the final HDPb-loaded emulgel selected as Pb-EG.

FTIR Evidence of Hydrolate–Matrix Interactions

FTIR analysis was used to investigate whether hydrolate incorporation altered the chemical organization of the nanostructured topical platforms. In both systems, the spectra preserved the main absorption bands associated with the polymeric and lipid components, indicating that hydrolate incorporation did not promote chemical degradation or covalent modification of the matrices. Instead, the observed changes were mainly associated with band broadening, intensity variation, and slight shifts in regions related to O–H stretching, C–O–C stretching, and polar functional groups, suggesting the predominance of non-covalent interactions such as hydrogen bonding and hydrophobic associations.[34–36]

For Ao-NG, the reference polymeric matrix exhibited characteristic bands of Pluronic F127, particularly the C–O–C stretching band around 1111 cm^{-1}, associated with the polyether backbone of the PEO and PPO blocks. After incorporation of HDAo, a broad band around 3400 cm^{-1} became more evident, indicating increased O–H stretching contributions and hydrogen bonding interactions. Additional spectral changes in the 1600–1650 cm^{-1} region and around 1450 cm^{-1} suggested the contribution of polar and unsaturated constituents from the hydrolate. The slight shift of the C–O–C band from approximately 1111 to 1109 cm^{-1} further supports interactions between HDAo constituents and ether groups of the Pluronic F127 matrix.[15,17,37]

For Pb-EG, the FTIR profile confirmed the successful integration of HDPb into the emulgel matrix without disrupting the structural identity of the polymer–lipid system. The hydrolate-loaded emulgel preserved the main bands associated with Pluronic F127, Carbopol 974P, and babassu oil, including C–H stretching bands related to aliphatic lipid chains, carbonyl stretching associated with ester groups from the oily phase, and the C–O–C stretching band of the polyether backbone. The main difference observed after HDPb incorporation was the increased intensity and broadening of the O–H stretching region, indicating stronger hydrogen bonding interactions and greater contribution of polar hydrolate constituents.[33,36,38]

The comparative FTIR findings indicate that HDAo and HDPb contributed to matrix

organization through formulation-dependent mechanisms. In Ao-NG, HDAo appeared to interact more directly with the hydrophilic polymeric network, as evidenced by the broad O–H band and the slight shift in the C–O–C region. In Pb-EG, HDPb was incorporated into a more complex polymer–lipid environment, where preservation of lipid and polymer bands suggests compatibility among Pluronic F127, Carbopol 974P, babassu oil, and hydrolate constituents. Therefore, both systems support the interpretation that plant-derived hydrolates act as active structuring components within nanostructured topical platforms, rather than merely as passive aqueous vehicles.[5,6]

The complete FTIR spectra of the reference matrices and hydrolate-loaded systems are provided in Figures S4 and S5. Therefore, the main text focuses on the comparative interpretation of the relevant absorption bands and their assignments, which are summarized in Table 4.

Table 4: Unified FTIR band assignments for the reference matrices and hydrolate-loaded Ao-NG and Pb-EG platforms.

Wavenumber (cm^{-1})	**Assignment**	**Interpretation**
Reference nanogel matrix		
∼2920	Symmetric C–H stretching	Aliphatic chains associated with PPO segments of Pluronic F127
∼1100–1111	C–O–C stretching	Ether groups from the PEO/PPO blocks of Pluronic F127
∼960–840	C–H bending	Structural vibrations of the polymeric matrix
Ao-NG: HDAo-loaded nanogel		
∼3400	O–H stretching broad band	Hydrogen bonding involving water, HDAo constituents, and the polymeric matrix
∼2920	Asymmetric C–H stretching	Hydrophobic PPO domains preserved after hydrolate incorporation
∼1600–1650	O–H bending / C=O stretching	Polar interactions and contribution of HDAo-derived constituents
∼1450	C=C stretching / C–H bending	Contribution of unsaturated or aliphatic hydrolate-associated groups
∼1109–1100	C–O–C stretching	Polyether backbone of Pluronic F127, with slight band shift suggesting hydrolate–polymer interactions
∼800–600	C–H bending	Structural organization of the hydrolate-loaded nanogel matrix
Reference emulgel matrix		
2893	C–H stretching	Lipid chains from babassu oil and aliphatic polymeric segments
1747	C=O stretching	Ester groups associated with the lipid phase
1452	C–H bending	Aliphatic structure of the polymer–lipid matrix
1267	C–O stretching	Contribution of the polymeric network
1172	C–O stretching	Contribution of the lipid phase
1110	C–O–C stretching	Polyether backbone of Pluronic F127
948	Skeletal vibration	Structural contribution of the polymeric matrix
844	C–H deformation	Structural order within the emulgel matrix
723	CH_2 rocking	Long-chain lipid structures
Pb-EG: HDPb-loaded emulgel		
3765	O–H stretching	Hydrolate-associated polar contribution
3415	O–H stretching	Increased hydrogen bonding after HDPb incorporation
2924	C–H stretching	Preservation of lipid chains in the polymer–lipid matrix
2854	C–H stretching	Maintenance of aliphatic structural organization
1745	C=O stretching	Ester groups preserved after hydrolate incorporation
1463	C–H bending	Maintained aliphatic contribution of the emulgel matrix
1346	O–H deformation	Hydrolate-associated signal and polar interactions
1282	C–O stretching	Non-covalent interactions within the hydrolate-loaded matrix
1110	C–O–C stretching	Pluronic F127 backbone preserved after HDPb incorporation
956	Skeletal vibration	Matrix structure preserved
842	C–H deformation	Stable polymer–lipid network organization

Reference nanogel matrix: selected blank nanogel matrix. Ao-NG: *Anacardium occidentale* hydrolate-loaded nanogel. Reference emulgel matrix: emulgel matrix without hydrolate. Pb-EG: *Pectis brevipedunculata* hydrolate-loaded emulgel. HDAo: *Anacardium occidentale* hydrolate. HDPb: *Pectis brevipedunculata* hydrolate. PEO: poly(ethylene oxide). PPO: poly(propylene oxide).

Thermal Behavior and Matrix Organization

DSC analysis was used to evaluate the thermal behavior of the reference matrices and hydrolate-loaded platforms, with emphasis on thermal transitions associated with Pluronic F127-based organization and possible changes induced by hydrolate incorporation. The complete thermograms are provided in the Supplementary Information, while the main thermal events and comparative interpretations are summarized in Table 5.

For the nanogel platform, the reference polymeric matrix exhibited an endothermic event at approximately 57 °C, attributed mainly to the melting of crystalline domains associated with the poly(ethylene oxide) blocks of Pluronic F127. After incorporation of HDAo, the Ao-NG formulation showed a shift of this endothermic event to approximately 54 °C, accompanied by reduced peak intensity. This behavior suggests that HDAo interfered with the regular packing of polymer chains, reducing the crystallinity of the matrix and promoting a more disordered but cohesive polymeric organization.[30,39,40]

The reduction in peak intensity observed for Ao-NG is consistent with the FTIR evidence of hydrogen bonding and hydrolate–polymer interactions. The presence of polar hydrolate constituents may disturb the organization of Pluronic F127 crystalline domains by interacting with ether groups and hydrated regions of the matrix. Therefore, the DSC profile supports the interpretation that HDAo was not merely dispersed within the nanogel, but contributed to the molecular reorganization of the thermoresponsive polymeric network.[17,31]

For the emulgel platform, both the reference emulgel matrix and Pb-EG exhibited a main endothermic transition around 55 °C, indicating preservation of the thermal behavior associated with the Pluronic F127-based system. However, Pb-EG showed a smoother and less intense thermal event compared with the corresponding emulgel without hydrolate. This attenuation suggests that HDPb incorporation increased matrix homogeneity and modulated polymer chain mobility, probably through additional hydration and hydrogen bonding interactions within the polymer–lipid network.[30,31,41]

Importantly, the absence of additional sharp peaks or new thermal events in Pb-EG in-

dicates that HDPb did not generate new crystalline phases or promote detectable thermal incompatibility within the emulgel matrix. Instead, the thermal profile suggests that the hydrolate was physically integrated into the system, preserving the polymer–lipid organization while contributing to a more homogeneous energy distribution. This result agrees with the FTIR findings, which indicated preservation of the main lipid and polymer bands after HDPb incorporation.[3,12]

From a comparative perspective, both platforms showed thermal changes compatible with hydrolate-induced modulation of matrix organization. In Ao-NG, HDAo promoted a clearer shift and attenuation of the Pluronic-related endothermic event, suggesting a stronger effect on polymer crystallinity in the hydrophilic nanogel matrix. In Pb-EG, HDPb mainly attenuated the thermal transition while preserving the characteristic behavior of the emulgel, indicating integration into a more complex polymer–lipid architecture. These findings reinforce the formulation-dependent role of hydrolates as functional components capable of influencing the thermal organization of nanostructured topical systems.[5,6]

The complete DSC thermograms of the reference matrices and hydrolate-loaded platforms are provided in Figures S6 and S7. Thus, the main text emphasizes the principal thermal events, hydrolate-induced changes, and comparative interpretation of matrix organization, as summarized in Table 5.

Table 5: Comparative summary of the main DSC findings for the reference matrices and hydrolate-loaded Ao-NG and Pb-EG platforms.

Platform	**Main thermal event**	**Effect of hydrolate incorporation**	**Interpretation**
Reference nanogel matrix	Endothermic event at approximately 57 °C	Not applicable	Melting of crystalline domains associated with Pluronic F127, mainly poly(ethylene oxide) blocks
Ao-NG	Endothermic event shifted to approximately 54 °C	Peak shift and reduced intensity after HDAo incorporation	Reduced crystallinity and polymeric reorganization due to hydrolate–matrix interactions
Reference emulgel matrix	Endothermic event around 55 °C	Not applicable	Thermal transition associated with Pluronic F127 micellization and matrix reorganization
Pb-EG	Endothermic event maintained around 55 °C with smoother profile	Attenuation of the thermal transition after HDPb incorporation	Improved matrix homogeneity and physical integration of hydrolate into the polymer–lipid network

HDAo: *Anacardium occidentale* hydrolate. HDPb: *Pectis brevipedunculata* hydrolate.

Morphological Features of Ao-NG and Pb-EG Platforms

SEM analysis was performed to evaluate the morphological organization of the hydrolate-loaded platforms and to identify structural differences associated with the nanogel and emulgel architectures. Representative SEM micrographs of the selected hydrolate-loaded platforms are shown in Figure 1. The images reveal clear morphological differences between the two systems, with Ao-NG exhibiting a predominantly compact lamellar organization, whereas Pb-EG displays a more heterogeneous polymer–lipid matrix with irregular aggregates and porous regions. Additional micrographs at different magnifications are provided in the Supplementary Information.

The Ao-NG platform exhibited a compact lamellar morphology, characterized by overlapping plate-like structures and absence of well-defined pores. This organization suggests that HDAo incorporation promoted a denser arrangement of the Pluronic F127/Carbopol 974P matrix, likely through hydrogen bonding and polar interactions between hydrolate

constituents and polymeric chains. This interpretation is consistent with the FTIR results, which indicated increased O–H stretching contributions and slight modification of the C–O–C region, as well as with the DSC profile showing reduced crystallinity and polymeric reorganization after hydrolate incorporation.[39,42,43]

In contrast, Pb-EG displayed a more heterogeneous and porous morphology, with interconnected regions and irregular surface domains. This morphology is consistent with the biphasic nature of the emulgel, in which the polymeric network, hydrolate-containing aqueous phase, and babassu oil droplets contribute collectively to matrix organization. The porous architecture observed for Pb-EG may also be related to water sublimation during freeze-drying, a common effect in hydrogel and emulgel systems containing hydrated polymeric domains.[3,12,44]

The morphological differences between Ao-NG and Pb-EG highlight the role of formulation architecture in determining the final organization of hydrolate-based topical systems. Ao-NG formed a more compact lamellar structure, compatible with a hydrophilic thermoresponsive nanogel matrix, whereas Pb-EG formed a porous polymer–lipid network, compatible with an emulgel system containing both aqueous and lipid domains. Therefore, although both platforms incorporated plant-derived hydrolates into Pluronic F127/Carbopol 974P-based matrices, the structural outcome depended strongly on the presence or absence of a lipid phase.

Taken together, the SEM, FTIR, and DSC findings demonstrate that hydrolate incorporation contributed to matrix organization in both systems, but through distinct formulation-dependent mechanisms. In Ao-NG, HDAo appeared to promote closer packing of the polymeric network, leading to a compact lamellar morphology. In Pb-EG, HDPb was integrated into a polymer–lipid matrix, generating a more porous and heterogeneous nanostructured morphology. These differences are relevant for topical formulation performance, as matrix compactness, porosity, and phase organization may influence hydration, retention, and the local availability of bioactive constituents.[4,14]

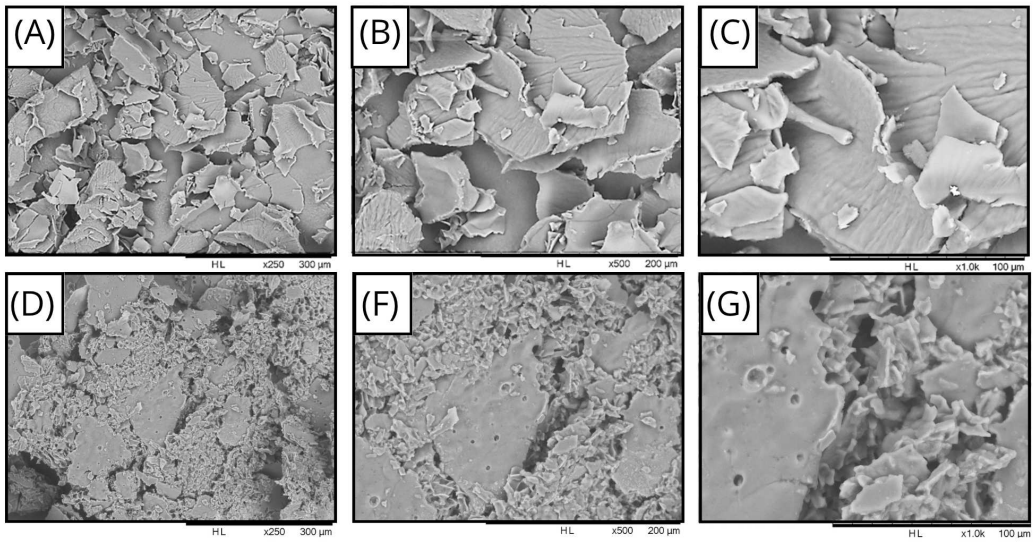

Figure 1: Scanning electron microscopy (SEM) micrographs of the hydrolate-loaded nanostructured topical platforms. (A–C) Ao-NG, corresponding to the *Anacardium occidentale* hydrolate-loaded nanogel, showing a compact lamellar morphology with overlapping plate-like structures at different magnifications. (D–G) Pb-EG, corresponding to the *Pectis brevipedunculata* hydrolate-loaded emulgel, showing a more heterogeneous polymer–lipid matrix with compact domains, irregular aggregates, and porous regions. The morphological differences indicate that hydrolate incorporation led to distinct structural organizations depending on the formulation architecture, with Ao-NG forming a predominantly lamellar polymeric network and Pb-EG forming a more heterogeneous emulgel matrix.

Comparative Antimicrobial Performance

The antimicrobial performance of the selected hydrolate-loaded platforms was evaluated against *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans*. Because NG, Ao-NG, EG, and Pb-EG are semisolid nanostructured systems, the assay was performed using fixed concentrations of 100% and 50%, and the results were interpreted as semiquantitative inhibitory responses under the experimental conditions rather than as conventional minimum inhibitory concentration values obtained from standardized serial dilutions. The antimicrobial responses are summarized in Table 6 and visually represented in Figure 2, using the same 0–3 resazurin-based metabolic activity scale.

For the nanogel platform, NG showed high microbial metabolic activity scores for all tested microorganisms at both 50% and 100%, indicating absence of inhibitory activity by

the reference nanogel matrix. In contrast, Ao-NG showed a concentration-dependent antimicrobial response. Ao-NG (100%) resulted in score 0 against *E. coli*, *S. aureus*, and *C. albicans*, indicating absence of detectable microbial metabolic activity under the assay conditions. Ao-NG (50%) resulted in score 1 for the three microorganisms, indicating low/moderate residual metabolic activity. These findings suggest that HDAo incorporation was the main factor associated with the antimicrobial performance of the Ao-NG platform, since the hydrolate-free NG matrix did not inhibit microbial growth at the evaluated concentrations.

For the emulgel platform, EG already showed antimicrobial activity, particularly at 100%, with score 0 against all tested microorganisms. At 50%, EG maintained score 0 against *S. aureus*, but showed score 1 against *E. coli* and *C. albicans*. This behavior indicates that the reference emulgel matrix itself contributed to the antimicrobial response, probably due to the presence of babassu oil in the polymer–lipid system. Babassu oil is rich in medium-chain saturated fatty acids, especially lauric, caprylic, and capric acids, which have been associated with antimicrobial effects and membrane-related interactions in previous studies. However, because isolated-oil assays and mechanistic antimicrobial experiments were not performed, this contribution should be interpreted as a formulation-level hypothesis rather than as direct mechanistic evidence.[25,26,45]

Pb-EG showed a broader inhibitory profile than EG at the lower tested concentration. Pb-EG (100%) resulted in score 0 against all microorganisms, similar to EG (100%). However, Pb-EG (50%) maintained score 0 against *S. aureus* and *C. albicans*, while showing score 1 only against *E. coli*. This result is particularly relevant for *C. albicans*, since EG (50%) showed residual metabolic activity, whereas Pb-EG (50%) maintained absence of detectable microbial metabolic activity. Therefore, HDPb incorporation appears to improve the antifungal performance of the emulgel, probably through the combined contribution of hydrolate-derived polar constituents and the babassu oil-containing polymer–lipid matrix.

From a comparative perspective, the antimicrobial results indicate that hydrolates contributed to biological performance through formulation-dependent mechanisms. In Ao-NG,

the antimicrobial effect was mainly associated with HDAo incorporation into a hydrophilic nanogel matrix, since NG showed no inhibitory response. In Pb-EG, antimicrobial activity reflected the combined contribution of the EG polymer–lipid matrix and HDPb incorporation, with the clearest hydrolate-associated improvement observed against *C. albicans* at 50%. These findings support the role of plant-derived hydrolates as functional bioactive components in nanostructured topical systems, particularly when incorporated into matrices capable of maintaining their local availability and interaction with microbial cells.[5,6,46?]

Table 6: Comparative antimicrobial response of hydrolate-loaded and reference topical platforms against selected microorganisms.

Platform/Formulation	**Condition**	***E. coli***	***S. aureus***	***C. albicans***
NG	50%	3	3	3
NG	100%	3	3	3
Ao-NG	50%	1	1	1
Ao-NG	100%	0	0	0
EG	50%	1	0	1
EG	100%	0	0	0
Pb-EG	50%	1	0	0
Pb-EG	100%	0	0	0
Growth control	Medium + inoculum	3	3	3
Sterility control	Medium only	0	0	0
Gentamicin	1 μg/mL	0	0	N/A
Amphotericin B	16 μg/mL	N/A	N/A	0

Semiquantitative scale based on resazurin response: 0, absence of detectable microbial metabolic activity; 1, low/moderate microbial metabolic activity; 2, intermediate microbial metabolic activity; 3, high microbial metabolic activity. N/A: not applicable. NG: reference nanogel matrix. Ao-NG: *Anacardium occidentale* hydrolate-loaded nanogel. EG: reference emulgel matrix. Pb-EG: *Pectis brevipedunculata* hydrolate-loaded emulgel.

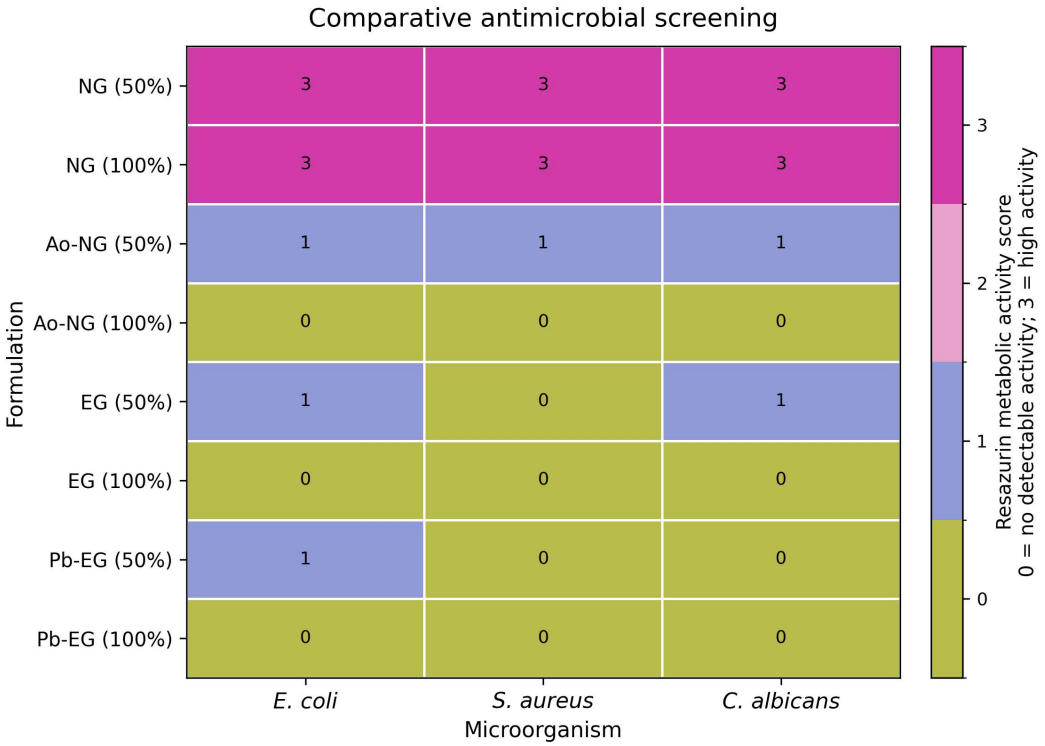

Figure 2: Heatmap representation of the semiquantitative antimicrobial screening results obtained by the resazurin assay, using a color scale adjusted to reflect the tones visually observed in the microplate wells. Rows indicate formulation and concentration, and columns indicate the tested microorganisms. Values correspond to semiquantitative metabolic activity scores, where lower values indicate lower metabolic activity and stronger inhibitory response, whereas higher values indicate greater microbial metabolic activity under the tested conditions.

Functional Role of Hydrolates in Nanostructured Topical Systems

The comparative evaluation of Ao-NG and Pb-EG demonstrates that plant-derived hydrolates can be incorporated into nanostructured topical platforms as functional formulation components rather than as inert aqueous residues. Although both systems were based on Pluronic F127 and Carbopol 974P, their distinct architectures resulted in different physicochemical, morphological, thermal, and antimicrobial profiles. Ao-NG represented a hydrophilic thermoresponsive nanogel platform, whereas Pb-EG represented a polymer–lipid emulgel containing babassu oil. This comparative design highlights how hydrolate functionality depends not only on the botanical source, but also on the formulation environment into

which the hydrolate is incorporated.[5,12,15,17]

In Ao-NG, the incorporation of HDAo produced relevant changes in the polymeric matrix, including FTIR evidence of hydrogen bonding, attenuation and displacement of the main DSC thermal event, and formation of a compact lamellar morphology. These findings suggest that HDAo interacted with the hydrophilic polymeric network and contributed to the supramolecular organization of the nanogel. The antimicrobial response further supports this interpretation, since NG showed no inhibitory activity, whereas Ao-NG (100%) produced absence of detectable microbial metabolic activity against all tested microorganisms. Therefore, the biological performance of Ao-NG appears to be mainly associated with the incorporation of HDAo into the thermoresponsive nanogel matrix.[30,31,46]

In Pb-EG, the presence of babassu oil introduced an additional formulation variable that influenced both matrix organization and antimicrobial performance. The EG matrix already showed antimicrobial activity, particularly at 100%, and maintained inhibition against *S. aureus* at 50%. This effect may be related to the lipid phase, since babassu oil is rich in medium-chain saturated fatty acids such as lauric, caprylic, and capric acids, which have been associated with antimicrobial activity in previous studies. However, this interpretation should be considered a formulation-level hypothesis, because isolated-oil antimicrobial assays and mechanistic membrane studies were not performed in the present work.[25,26,45]

Despite the intrinsic contribution of the EG matrix, HDPb incorporation improved the antimicrobial profile of the emulgel, especially against *C. albicans* at 50%. While EG (50%) showed residual metabolic activity against *C. albicans*, Pb-EG (50%) resulted in absence of detectable microbial metabolic activity. This difference suggests that HDPb enhanced the antifungal performance of the polymer–lipid platform, probably through the combined effects of hydrolate-derived polar constituents, matrix hydration, and babassu oil-associated lipid domains. Therefore, Pb-EG illustrates how hydrolates may act synergistically with lipid-containing matrices to modulate biological response.[5,6,46]

The comparison between Ao-NG and Pb-EG also reinforces the importance of formulation

architecture in determining hydrolate performance. In the hydrophilic Ao-NG platform, HDAo appeared to act more directly on the polymeric network, influencing thermal behavior, morphology, and antimicrobial response. In the polymer–lipid Pb-EG platform, HDPb was integrated into a more complex matrix in which the lipid phase contributed to both structural organization and biological activity. Thus, hydrolate incorporation should be understood as a formulation-dependent strategy, where the final performance emerges from the interaction between plant-derived aqueous constituents, polymers, lipid components, and the physical organization of the semisolid matrix.[3,4,14]

From a sustainability perspective, the use of HDAo and HDPb supports the valorization of hydrolates as underexplored co-products of plant processing. Hydrolates are often generated during hydrodistillation and may be undervalued or discarded despite containing water-soluble volatile and non-volatile constituents with potential biological relevance. Their incorporation into nanostructured topical systems provides a route to transform these aqueous co-products into value-added formulation ingredients, aligning topical formulation development with principles of green chemistry, circular economy, and biodiversity-based innovation.[5,6,8,9]

Overall, the integrated results indicate that both hydrolate-loaded platforms were physically stable, structurally organized, and biologically active under the evaluated conditions. Ao-NG was more directly dependent on HDAo incorporation for antimicrobial performance, whereas Pb-EG combined HDPb with a babassu oil-containing polymer–lipid matrix that already displayed intrinsic antimicrobial contribution. These findings support the hypothesis that plant-derived hydrolates can be rationally used as functional components in sustainable nanostructured topical platforms. Nevertheless, further studies involving chemical profiling of hydrolate constituents, release and permeation assays, quantitative antimicrobial tests, and mechanistic biological evaluations are required to confirm their translational potential.[5,6,46**?**]

Conclusions

This study demonstrated the feasibility of incorporating plant-derived hydrolates into nanostructured topical platforms as functional formulation components. Ao-NG and Pb-EG were successfully developed as complementary hydrolate-based systems using Pluronic F127 and Carbopol 974P as structuring polymers. Ao-NG represented a hydrophilic thermoresponsive nanogel incorporating HDAo, whereas Pb-EG represented a polymer–lipid emulgel incorporating HDPb and babassu oil. Both platforms showed physical stability and formulation-dependent structural organization, supporting the technological potential of hydrolates as value-added aqueous co-products.

Physicochemical characterization indicated that hydrolate incorporation influenced the organization of both matrices. FTIR results suggested non-covalent interactions involving hydrolate constituents and polymeric functional groups, while DSC analysis showed changes in thermal transitions compatible with hydrolate-induced modulation of matrix organization. SEM analysis further confirmed distinct morphological profiles, with Ao-NG exhibiting a compact lamellar structure and Pb-EG showing a more heterogeneous polymer–lipid matrix with porous regions. These findings demonstrate that the final organization of hydrolate-loaded systems depends strongly on formulation architecture.

The antimicrobial screening showed that hydrolate incorporation contributed to the biological performance of the formulations. Ao-NG (100%) inhibited detectable microbial metabolic activity against *E. coli*, *S. aureus*, and *C. albicans*, whereas NG showed no inhibitory response. In the emulgel platform, EG already displayed antimicrobial contribution, probably associated with the babassu oil-containing polymer–lipid matrix, while Pb-EG improved the inhibitory profile at 50%, particularly against *C. albicans*. These results indicate that hydrolates may contribute to antimicrobial performance either as the main bioactive component in hydrophilic nanogels or in combination with lipid-containing matrices in emulgels.

Overall, the results support the use of plant-derived hydrolates as sustainable and func-

tional ingredients for nanostructured topical systems. The comparative approach adopted in this study highlights that hydrolate performance is formulation-dependent and influenced by the interaction between botanical source, polymeric matrix, lipid phase, and semisolid architecture. Further studies should include chemical profiling of hydrolate constituents, release and skin permeation assays, standardized quantitative antimicrobial tests, cytocompatibility evaluation, and mechanistic biological studies to confirm the translational potential of these platforms for topical applications.

Conflicts of Interest

The authors declare no conflict of interest.

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