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DP2-DP6-Enriched Maritime Pine Bark Microcapsules Support Keratinocyte Redox Control and a Nutritional Photoprotection Framework

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Abstract: Oral photoprotection depends on repeated delivery of compounds that can influence the skin response to ultraviolet stress. We examined a BCLC maritime pine bark microcapsule enriched in DP2-DP6 oligomeric proanthocyanidins. The reference material contained 62.4% DP2-DP6 within total proanthocyanidins, with low catechin/epicatechin and DP $\geq$ 10 fractions. In H₂O₂-challenged HaCaT keratinocytes, intracellular ROS fell from the model value of 100% to 78.4%, 68.5% and 60.7% at 25, 50 and 100 μ g/mL; cell viability remained above 93%. During simulated digestion, DP2-DP6 retention was 86.8% after the gastric phase and 78.6% after the intestinal phase. Human studies of standardized French maritime pine bark extract include an eight-week trial in which the ultraviolet dose required for one minimal erythema dose increased during supplementation and a randomized double-blind crossover study in outdoor workers reporting protection against seasonal skin darkening and deterioration of hydration/barrier parameters. The formulation and cell data place ingredient stability and keratinocyte redox control alongside established human photobiology endpoints for BCLC-specific evaluation.

Keywords: photoprotection; ultraviolet radiation; maritime pine bark; oligomeric proanthocyanidins; keratinocyte; ROS; minimal erythema dose

1. Introduction

Cutaneous photodamage is not produced by a single pathway. Ultraviolet radiation changes cellular redox balance, promotes inflammatory signaling, and contributes to matrix remodeling; UVA is especially relevant to oxidative stress, whereas UVB is a major driver of erythema. Nutritional photoprotection is therefore usually studied as a repeated-exposure strategy that modifies the biological response to light rather than as a replacement for topical photoprotection. French maritime pine bark extracts are relevant to this question because their procyanidin-rich fractions have been discussed in relation to antioxidant activity and a broader range of biological effects [1], [2].

Human studies have approached oral photoprotection with several distinct endpoints. Saliou et al. followed 21 volunteers for eight weeks and found that the ultraviolet dose required to produce one minimal erythema dose increased during supplementation [3]. Zhao et al. subsequently used a randomized, placebo-controlled, double-blind crossover design in 76 outdoor workers; 100 mg/day was associated with protection against seasonal darkening and with favorable changes in hydration, transepidermal water loss and viscoelastic measures [4]. Furumura et al. reported changes in photoaging scores and age-spot pigmentation in 112 women [5], while Marini et al. used hydration and elasticity measurements during a 12-week oral-supplementation study [6]. The studies did not use an identical clinical question, but together they show why erythema, color and barrier measurements can be useful when an oral skin-support ingredient is evaluated.

Mechanistic and exposure data add a second layer to those clinical observations. Plasma obtained after oral maritime pine bark extract intake has been reported to reduce NF- κ B activation and MMP-9 secretion in an ex vivo system [7]. Separate pharmacokinetic work identified parent compounds and metabolites in plasma after single and repeated oral dosing [8]. These findings do not establish a photoprotective effect for every pine-bark preparation; they do show that biological interpretation should take actual exposure into account rather than rely only on the nominal amount of total proanthocyanidins in a capsule.

The chemical profile of the extract is also relevant. Comparative work on Pinus bark extracts has shown differences in procyanidin composition alongside antioxidant measurements [9], and the broader procyanidin literature indicates that absorption and metabolic fate vary with degree of polymerization [10]. Reviews of maritime pine bark preparations likewise describe substantial variation in composition, experimental setting and reported biological activity [11], [12], [13], [14]. For an oligomer-enriched material, this makes chain-length specification more than an analytical detail: it defines the material that enters stability, digestion and exposure studies.

Skin-cell experiments provide a practical bridge between composition and human endpoints. Leis Ayres et al. examined pigmentation-related signaling and tyrosinase activity in cultured melanocytes exposed to ultraviolet, infrared and visible light [15]. The present work uses a different cellular question, focusing on oxidative stress in HaCaT keratinocytes, and couples that response with digestive retention of a defined DP2-DP6 fraction. The BCLC material was therefore evaluated as a formulation with a specified oligomer distribution rather than as a generic pine bark extract. We measured keratinocyte ROS and viability, followed DP2-DP6 through simulated gastric and intestinal phases, and then used the published human literature to identify photobiology endpoints that are suitable for later formulation-specific testing.

2. Materials and Methods

2.1 BCLC ingredient. Maritime pine bark extract was prepared by aqueous-ethanol extraction, macroporous-resin gradient fractionation, 3-10 kDa membrane removal of high polymers, 300-500 Da concentration of the oligomer-rich retentate and composite-wall microencapsulation. The reference material contained $74.8 \pm 2.1\%$ total proanthocyanidins, $62.4 \pm 1.8\%$ DP2-DP6, $5.1 \pm 0.4\%$ combined catechin/epicatechin, $7.3 \pm 0.6\%$ DP ≥ 10 material, and water activity of 0.31 ± 0.01 .

2.2 Keratinocyte oxidative-stress model. Human HaCaT keratinocytes were challenged with H₂O₂. BCLC extract was tested at 25, 50 and 100 $\mu\text{g/mL}$. Cell viability and intracellular ROS were measured with DCFH-DA fluorescence; the H₂O₂ model was normalized to 100% ROS.

2.3 Digestive stability. Microcapsule samples were exposed to simulated gastric fluid for 60 min and then to simulated intestinal fluid for 120 min. DP2-DP6 and total proanthocyanidin retention were measured after each phase.

2.4 Clinical literature synthesis. PubMed and publisher databases were searched through August 2026 using terms related to Pinus pinaster, maritime pine bark, ultraviolet exposure, erythema, photoprotection, skin darkening, skin barrier and randomized trials. Human studies with direct light-response or skin-environmental endpoints were prioritized.

3. Results

3.1 Keratinocyte redox response. H₂O₂ challenge produced a model ROS value of $100.0 \pm 3.5\%$ and reduced cell viability to $79.2 \pm 2.7\%$. With BCLC at 25, 50 and 100 $\mu\text{g/mL}$, ROS was $78.4 \pm 2.8\%$, $68.5 \pm 2.6\%$ and $60.7 \pm 2.4\%$. Viability at the same concentrations was $93.5 \pm 3.0\%$, $94.1 \pm 3.1\%$ and $93.6 \pm 2.9\%$.

3.2 Gastrointestinal-phase retention. The reference microcapsule retained $86.8 \pm 2.5\%$ of DP2-DP6 after the simulated gastric phase and $78.6 \pm 2.2\%$ after the intestinal phase. Total proanthocyanidin retention at the end of the intestinal phase was $80.4 \pm 2.3\%$. The ordinary extract retained $48.5 \pm 2.0\%$ of DP2-DP6 after the intestinal phase; the maltodextrin-only microcapsule comparator retained $58.2 \pm 2.1\%$.

3.3 Human photoprotection context. Saliou et al. studied 21 volunteers receiving 1.10 mg/kg/day French maritime pine bark extract for four weeks followed by 1.66 mg/kg/day for another four weeks. The UV dose required to produce one MED increased significantly during supplementation [3]. Zhao et al. conducted a randomized, placebo-controlled, double-blind crossover intervention in 76 outdoor workers using 100 mg/day for 12 weeks and reported protection against seasonal skin darkening together with favorable hydration, TEWL and viscoelastic responses [4]. Furumura et al. reported improvement in clinically graded photoaging and age-spot pigmentation with oral pine bark extract in 112 women [5].

Table 1. Gastrointestinal-phase retention of proanthocyanidins

Preparation	DP2-DP6 retention: gastric 60 min (%)	DP2-DP6 retention: intestinal 120 min (%)	Total PAC retention: intestinal 120 min (%)
Ordinary extract comparator	61.2 ± 2.4	48.5 ± 2.0	50.6 ± 2.2
Single-wall comparator	70.4 ± 2.3	58.2 ± 2.1	60.1 ± 2.0
BCLC F1	86.8 ± 2.5	78.6 ± 2.2	80.4 ± 2.3
BCLC F2	84.1 ± 2.4	75.2 ± 2.1	77.5 ± 2.2
BCLC F3	82.5 ± 2.3	72.8 ± 2.0	74.6 ± 2.1

Table 2. Human studies informing nutritional photoprotection endpoints

Study	Design	Exposure	Photoprotection / skin relevance
Saliou et al., 2001 [3]	Clinical trial; 21 volunteers	1.10 mg/kg/day for 4 wk, then 1.66 mg/kg/day for 4 wk	UV dose required for 1 MED increased during supplementation
Zhao et al., 2021 [4]	Randomized, placebo-controlled, double-blind crossover; n=76	100 mg/day; 12 weeks	Protected against seasonal skin darkening and deterioration in hydration/TEWL; improved viscoelastic properties
Furumura et al., 2012 [5]	Randomized oral supplementation study; n=112	40 or 100 mg/day depending study arm	Photoaging scores and age-spot pigmentation improved

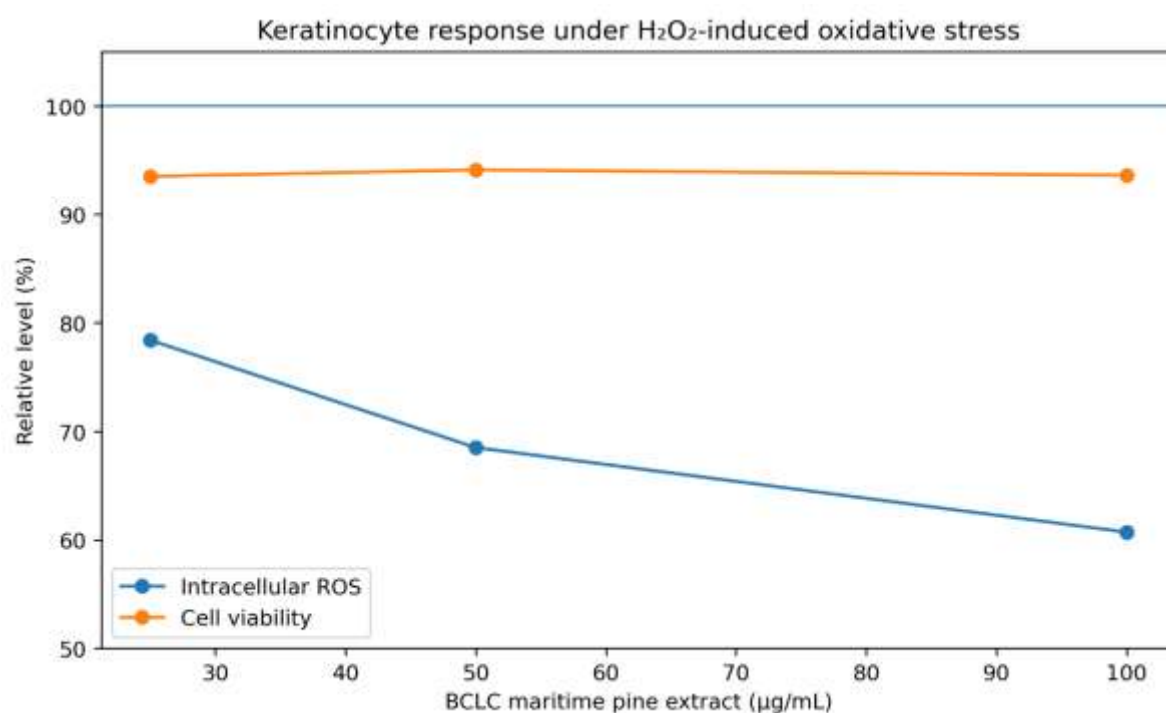


Figure 1. Intracellular ROS and cell viability in H_2O_2 -challenged HaCaT keratinocytes treated with the BCLC DP2-DP6-enriched maritime pine bark extract.

4. Discussion

In the HaCaT model, the concentration series separated redox response from loss of viability. ROS fell from $100.0 \pm 3.5\%$ in the H_2O_2 model to $60.7 \pm 2.4\%$ at $100 \mu\text{g/mL}$, while viability at that concentration was $93.6 \pm 2.9\%$. Keratinocytes are directly involved in UV-responsive redox and inflammatory signaling. Mechanistic work with maritime pine bark extract has described antioxidant activity [1], [2], and plasma collected after oral intake has been shown ex vivo to reduce NF- κ B activation and MMP-9 secretion [7].

The digestion data address a different problem: the material assayed at manufacture is not necessarily the same distribution presented to the intestine. BCLC F1 retained $86.8 \pm 2.5\%$ of

DP2-DP6 after the gastric phase and $78.6 \pm 2.2\%$ after the intestinal phase. The ordinary extract reached $48.5 \pm 2.0\%$ after the intestinal phase, and the single-wall comparator reached $58.2 \pm 2.1\%$. Human pharmacokinetic observations [8] and the wider procyanidin ADME literature [10] make chain-length-specific exposure a useful measurement rather than assuming that total proanthocyanidins alone predict systemic availability.

The clinical studies supply concrete skin endpoints. Saliou et al. used MED and found that the UV dose needed for one MED increased during supplementation [3]. Zhao et al. tested 100 mg/day for 12 weeks under everyday outdoor exposure and reported less seasonal skin darkening together with favorable hydration, TEWL and viscoelastic responses [4]. Furumura et al. documented changes in photoaging scores and pigmented age spots [5]. These designs point to MED or standardized erythema as primary choices, with colorimetry, TEWL and hydration as useful complementary measurements.

BCLC can be tested on its own DP2-DP6 specification while drawing on those established methods. Reviews of French maritime pine bark extracts describe a broad antioxidant and anti-inflammatory literature but also substantial variation in extract composition and clinical setting [11], [12], [13], [14]. Light-responsive melanocyte experiments provide another laboratory endpoint relevant to cutaneous environmental stress [15]. For the present formulation, the useful bridge is between a measured oligomer distribution, its retention through digestion and a prespecified human skin response.

5. Study Considerations and Future Directions

An 8-12 week randomized BCLC study could use MED or standardized UV erythema as the primary endpoint. Erythema index, TEWL, hydration, L^*/ITA° , seasonal skin darkening and selected systemic or skin-derived oxidative-stress biomarkers could be collected at the same visits. Plasma phenolic metabolites should be sampled alongside batch-specific DP2-DP6 measurements so that exposure kinetics can be related to the ingredient actually administered.

6. Conclusion

The DP2-DP6-enriched BCLC microcapsule lowered intracellular ROS in H_2O_2 -challenged keratinocytes while maintaining cell viability and retained 78.6% of DP2-DP6 after the simulated intestinal phase. Human studies with standardized French maritime pine bark extracts show that MED, seasonal skin darkening, hydration, TEWL and photoaging-related outcomes can be measured during oral supplementation. These endpoints can now be paired with the defined BCLC oligomer profile in formulation-specific photoprotection studies.

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