

Article

Plant-Derived By-Products as Multifunctional Ingredients in Sustainable Cosmetic Emulsions: Concentration-Dependent Effects of Orange Peel Microparticles

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Abstract

The introduction of regulations restricting the use of microplastics in cosmetics, combined with the growing demand for sustainable cosmetic formulations and the continuing consumer interest in naturally derived ingredients, increases the need to develop alternative functional materials. The aim of this study was to evaluate the effect of plant-derived microparticles obtained from agro-industrial fruit by-products (orange peel) on the properties of cosmetic emulsions as a function of their concentration. Model emulsions containing 0–5% orange peel microparticles were prepared and analyzed in terms of physicochemical properties (viscosity, pH, color, stability), sensory characteristics, antioxidant activity (DPPH), and their impact on skin biophysical and optical parameters. Results showed that increasing microparticle concentration significantly enhanced emulsion viscosity (from 17,000 to 36,000 mPa·s) and antioxidant activity (from 13% to 77% DPPH inhibition). Application studies revealed a 54% increase in skin hydration and a fourfold reduction in transepidermal water loss (from 24 to 6 g/m²/h) for formulations with the highest concentration. However, concentrations containing 3–5% led to reduced emulsion stability. Although higher concentrations (4–5%) provided stronger antioxidant and skin-related effects, the 2% formulation provided the most favorable balance between physical stability, functional performance, sensory acceptance, and formulation appearance. These findings indicate that natural microparticles derived from orange peel can serve as multifunctional, sustainable ingredients in cosmetic emulsions, providing structuring, antioxidant, and skin-barrier-supporting effects.

Keywords: plant-derived microparticles; orange peel; agro-industrial by-products; sustainable cosmetics; cosmetic emulsions; antioxidant activity; transepidermal water loss (TEWL)



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1. Introduction

In recent years, tightening regulatory requirements have significantly changed the way cosmetic products are formulated. The restrictions on intentionally added microplastics introduced by the European Chemicals Agency under the REACH regulation, and formally implemented through Commission Regulation (EU) 2023/2055, have pushed manufacturers to look for alternatives to synthetic polymer particles that have long served as stabilizers, thickeners, and sensory modifiers [1–4]. This regulatory pressure, together with growing consumer demand for more natural and sustainable cosmetics, has accelerated the search for effective replacements [5–7].

At the same time, the concept of sustainability in the cosmetics industry has moved towards a circular economy model [8]. Instead of treating agro-industrial by-products as waste, there is increasing interest in turning them into valuable raw materials [9]. This approach not only contributes to waste reduction but also creates opportunities for developing multifunctional ingredients that combine technological and biological activities within a single raw material. Such ingredients are increasingly sought after in cosmetic formulations due to their potential to improve product performance while reducing formulation complexity [10].

The fruit processing industry generates around 0.5 billion tons of waste annually, and citrus fruits are particularly interesting in this context [11]. With global production exceeding 150 million tons per year [12], 55–70% of the processed fruit mass ends up as peels, pulp, and seeds [11]. Among these by-products, orange peel stands out because of its high content of polysaccharides, phenolic compounds, and essential oils, which offer antioxidant, antimicrobial, and structuring properties [13,14].

Orange peel was selected as a model plant-derived by-product because it is generated in large quantities worldwide, is readily available throughout the year, and combines a high content of structural polysaccharides with naturally occurring bioactive compounds. In contrast to many other fruit-processing by-products, orange peel contains both insoluble fibrous components that may contribute to emulsion structuring and surface modification, as well as antioxidant compounds that may provide additional functional benefits. This unique composition makes orange peel a particularly attractive candidate for the development of multifunctional cosmetic ingredients [15].

In addition to these compounds, orange peel contains cellulose, hemicellulose, pectin, flavonoids, and carotenoids, which may influence the rheological behavior of formulations and provide additional skin-related benefits. Owing to their porous structure and high surface area, micronized plant particles can also interact with both the continuous phase of emulsions and the skin surface, potentially affecting viscosity, stability, hydration, and sensory properties [16].

When micronized, such materials can be incorporated into formulations not only as functional particles but also as carriers of bioactive substances [17].

Parallel to these developments, there has been growing interest in the role of solid particles in emulsion systems. Numerous studies have demonstrated that plant-derived particles can influence emulsion stability, rheological behavior, and sensory properties through their interactions with the continuous phase and the oil–water interface [18,19]. In particular, research on particle-stabilized and Pickering emulsions has provided valuable insight into the mechanisms by which solid particles affect emulsion structure and performance. Although the formulations investigated in the present study were conventional oil-in-water emulsions containing a complete emulsifying system rather than Pickering emulsions, findings from particle-stabilized emulsion research remain relevant for understanding the potential contribution of plant-derived microparticles to formulation properties. Therefore, the present work focuses not on the development of Pickering systems but on evaluating the multifunctional effects of orange peel microparticles when incorporated into conventional cosmetic emulsions [20].

At the same time, consumers increasingly perceive upcycled ingredients as environmentally responsible alternatives to conventional cosmetic raw materials [8]. This trend has encouraged cosmetic manufacturers to explore plant-derived particles not only as sustainable ingredients but also as potential substitutes for synthetic fillers, texturizing agents, and sensory modifiers commonly used in cosmetic emulsions [20].

Plant-derived powders and particulate materials have already been investigated in various cosmetic applications, including formulations containing oat, rice, seed, shell, and

other agricultural by-products. These studies have demonstrated their potential to influence sensory characteristics, rheological behavior, and selected skin-related properties. However, most available reports focus on specific formulation aspects or single performance parameters. In contrast, information regarding the concentration-dependent effects of micronized orange peel by-products across a broad range of physicochemical, sensory, antioxidant, and skin-related parameters remains limited. Therefore, the novelty of the present study lies not in the use of plant-derived particles itself but in the systematic evaluation of orange peel microparticles as multifunctional cosmetic ingredients over a wide concentration range and across multiple formulation and performance characteristics [8,20].

In particular, we still lack a detailed understanding of how different concentrations of such particles influence key parameters such as viscosity, physical stability, sensory properties, antioxidant activity, and skin-related effects like hydration and barrier function [20–22]. The optimal concentration range that balances stability and performance has not been well established [23].

The aim of this study was therefore to investigate the concentration-dependent effects of microparticles obtained from orange peel—a major agro-industrial by-product—on cosmetic emulsions. Special attention was paid to their impact on physicochemical properties, sensory performance, antioxidant capacity, and selected skin biophysical parameters, in order to identify the most promising concentration range for practical use.

2. Materials and Methods

2.1. Materials

Model oil-in-water (O/W) emulsions were prepared using cosmetic-grade raw materials. The aqueous phase consisted of Aqua, Glycerin (Glicerina 99.5, SABO S.P.A., Levate, Italy), Xanthan Gum (Fufeng Group, Binzhou, China), and Polyglyceryl-4 Laurate/Sebacate and Polyglyceryl-6 Caprylate/Caprates (Natragem S140 NP, Croda, Goole, UK). The oil phase contained Caprylic/Capric Triglyceride (Crodamol GTCC, Croda, Goole, UK), Shea Butter Ethyl Esters (Lipex Shealight, AAK Sweden AB, Karlshamn, Sweden), Cetearyl Olivates/Sorbitan Olivates (Olivem 1000, Hallstar, Milan, Italy), and Cetearyl Alcohol (Lanette O, BASF, Ludwigshafen, Germany). The preservative system consisted of Potassium Sorbate/Sodium Benzoate/Water (KEM BS, Akema, Novara, Italy).

Orange peel microparticles (Vitacel® CS 7 Orange, JRS Rettenmaier, Rosenberg, Germany) were used as a functional ingredient in the formulations. Vitacel® CS 7 Orange is a natural, bio-based powder obtained from mechanically processed orange peel (INCI: Citrus Aurantium Dulcis Peel Powder). The ingredient is derived from food industry by-products and is composed primarily of orange dietary fibers. According to the supplier, the material is characterized by a beige color, fine powder appearance, bulk density of 150–250 g/L, moisture content below 7%, and pH ranging from 3.0 to 6.5. The median particle size distribution is reported as 2–10 µm. Vitacel® CS 7 Orange is described as a multifunctional cosmetic ingredient with mattifying, smoothing, slip-enhancing and sensory-modifying properties and can be used as a sustainable alternative to conventional powders such as silica, PMMA, nylon, polyethylene and silicone-based powders. The ingredient is COSMOS approved and certified as vegan, Halal and Kosher. The material was used as received without further modification.

2.2. Formulation of Emulsions

Seven model O/W emulsions were prepared, differing only in the concentration of orange peel microparticles: 0%, 0.5%, 1%, 2%, 3%, 4%, and 5% *w/w*. The control formulation did not contain microparticles. In all formulations, the concentrations of the oil phase components, emulsifying system, thickener, humectant, and preservative system

remained constant, while the water content was adjusted according to the concentration of orange peel microparticles, as shown in Table 1.

Table 1. Composition of model emulsions (% *w/w*).

Phase	Ingredient [INCI]	Concentration [% <i>w/w</i>]						
		P_B	P_0.5	P_1	P_2	P_3	P_4	P_5
A	Xanthan Gum				0.6			
	Glycerin				2			
	Aqua				42.2			
	Potassium Sorbate, Sodium Benzoate				0.2			
B	Citrus Aurantium Dulcis Peel Powder	-	0.5	1	2	3	4	5
	Aqua	-	2	4	8	12	16	20
C	Caprylic/Capric Triglyceride				6			
	Shea Butter Ethyl Esters				2			
	Polyglyceryl-4 Laurate/Sebacate				2			
	Polyglyceryl-6 Caprylate/Caprates							
	Cetearyl Olivates, Sorbitan Olivates				3			
	Cetearyl Alcohol				7			
	Aqua	34.7	32.3	29.7	24.7	19.7	14.7	9.7
	Potassium Sorbate, Sodium Benzoate, Aqua				0.3			

The emulsions were prepared according to a three-phase procedure involving the preparation of the aqueous phase (A), microparticle dispersion phase (B), and oil phase (C).

In the first step, xanthan gum was pre-dispersed in glycerin and subsequently added to distilled water containing dissolved Potassium Sorbate/Sodium Benzoate. The aqueous phase was heated to approximately 60 °C under continuous stirring until complete hydration of the polymer was achieved and a homogeneous gel-like system was obtained. After cooling to room temperature, Polyglyceryl-4 Laurate/Sebacate and Polyglyceryl-6 Caprylate/Caprates were incorporated into the aqueous phase and mixed until complete dispersion.

Separately, the oil phase containing Caprylic/Capric Triglyceride, Shea Butter Ethyl Esters, Cetearyl Olivates/Sorbitan Olivates, and Cetearyl Alcohol was heated in a water bath to 70 °C and stirred until all solid components were completely melted and a uniform phase was obtained.

Orange peel microparticles were dispersed separately in the appropriate amount of distilled water according to the formulation composition. The dispersion was mixed until complete wetting of the particles was achieved.

The aqueous phase was then gradually added to the oil phase under continuous mechanical stirring. The resulting pre-emulsion was mixed during cooling to approximately 25 °C. Subsequently, the previously prepared dispersion of orange peel microparticles was incorporated into the system.

The emulsions were then homogenized using a rotor–stator homogenizer (T 18 digital Ultra-Turrax®, IKA, Staufen, Germany). Homogenization was performed at room temperature (approximately 25 °C) at a rotational speed of 10,000 rpm for 3 min. During homogenization, the temperature of the samples was monitored and did not exceed 30 °C.

After homogenization, the formulations were visually inspected to confirm homogeneity and absence of visible agglomerates. The prepared emulsions were transferred into glass containers and stored at 20–22 °C for 7 days prior to physicochemical, stability, antioxidant, sensory, and skin-related analyses in order to allow stabilization of the emulsion structure.

2.3. Physicochemical Analysis

2.3.1. Viscosity

Dynamic viscosity was measured using a Brookfield DV-I+ rotational viscometer (AMETEK Brookfield, Middleboro, MA, USA). Approximately 200 g of each emulsion was placed in a 250 mL beaker, avoiding air incorporation. Measurements were performed at 22 °C using spindle no. 3 or 4, selected according to sample consistency and torque range. Viscosity was recorded at 10, 50, and 100 rpm. For each sample and speed, five measurements were performed, and the mean value was calculated. Results are expressed as mPa·s.

2.3.2. pH

The pH of the emulsions was measured using a CP-401 pH meter (Elmetron, Zabrze, Poland). Before analysis, the instrument was calibrated using standard buffer solutions. The electrode was rinsed with distilled water and dried between measurements. Measurements were performed at 22 °C, and each sample was analyzed in triplicate. The final result was expressed as the mean value.

2.3.3. Color of Emulsions

Color parameters were measured using a CR-400 colorimeter (Konica Minolta, Tokyo, Japan) in the CIE L*a*b* color space. The device was calibrated before measurements using a white calibration plate. Each sample was measured three times, and the mean values of L*, a*, and b* were calculated. Total color difference (ΔE) was calculated according to the CIE L*a*b* formula (Commission) [24].

2.3.4. Physical Stability

Physical stability was evaluated using a Turbiscan LabCooler (Formulation, Toulouse, France). Samples were placed in cylindrical glass measurement vials and scanned over the full sample height. Measurements were carried out over 36 days, with scans performed every 4–6 days. During the test, samples were stored at 40 °C. Changes in backscattering and transmission profiles were analyzed using Turbisoft 2.0 software.

2.4. Antioxidant Activity by DPPH Assay

Antioxidant activity was determined using the DPPH radical scavenging assay according to the method described by Brand-Williams et al. [25]. A methanolic DPPH solution with an initial absorbance of 0.9–1.0 at 515 nm was prepared.

For analysis, 0.5 mL of emulsion sample was mixed with 1.5 mL of DPPH solution, vortexed for 30 s, and incubated for 10 min in the dark at room temperature. The samples were then centrifuged (13,200 rpm, 5 min), and the absorbance of the supernatant was measured at 515 nm using a Tecan Infinite M200 spectrophotometer (Tecan Group Ltd., Männedorf, Switzerland).

A control sample (DPPH solution without sample) was used. All measurements were performed in triplicate. In addition, blank samples containing the corresponding formulation without DPPH solution were prepared and analyzed to account for potential background absorbance and optical interference originating from the emulsion matrix. The measured values were used for correction of the final absorbance readings.

The radical scavenging activity was calculated as

$$\text{DPPH inhibition [\%]} = [(A_0 - A_1)/A_0] \times 100 \quad (1)$$

where A_0 is the absorbance of the control and A_1 is the absorbance of the sample.

2.5. Skin Measurements

Skin measurements, including skin hydration, transepidermal water loss (TEWL), skin color, and skin lubrication, were performed on healthy adult volunteers under controlled laboratory conditions. Skin hydration, TEWL, and skin color measurements were conducted on the volar forearm of 30 volunteers. Skin lubrication measurements were performed on the faces of 30 participants. For facial measurements, the study group included 7 individuals with dry skin, 13 with normal skin, and 10 with combination/oily skin. Skin type classification was performed only for facial measurements, as facial sebum production represents a key physiological parameter in these assessments. Participants were not classified according to skin type for forearm measurements because the volar forearm is characterized by a low density of sebaceous glands and is not typically used for categorization of skin as dry, normal, or oily.

Inclusion criteria were age ≥ 18 years, good general health, absence of visible skin lesions in the test area, and provision of informed consent. Exclusion criteria included active skin diseases within the test area, epidermal damage, use of topical medications on the test sites, and known allergy to any ingredient of the tested formulations.

Before measurements, participants acclimatized for 20 min at 22 °C and 40–45% relative humidity.

Skin hydration and transepidermal water loss measurements were performed using a within-subject repeated-measures design with multiple test sites on the same forearm. Separate test areas were marked on the volar forearm of each participant, and each area received a different formulation, including the base formulation (P_B). Thus, all formulations were evaluated on every participant under identical environmental conditions, allowing intra-individual comparison of the tested products. The assignment of formulations to individual test sites was varied between participants. Formulations were not applied to fixed anatomical locations, thereby minimizing potential bias associated with site-specific differences in skin properties.

For the measurement of skin hydration and transepidermal water loss, test areas measuring 5×5 cm were marked on the forearm. Each formulation was applied to the designated test area at a dose of approximately 2 mg/cm^2 prior to instrumental measurements.

For facial skin lubrication, a split-face design was applied. The test formulation was applied to one half of the face at a dose of approximately 2 mg/cm^2 (corresponding to approximately 0.5 g per half-face), while the contralateral side remained untreated and served as the control area. Before testing, participants cleansed their faces using a standard cleanser and subsequently applied a moisturizing toner to the entire face. Following product application, participants did not use makeup, sunscreen products, or additional skincare products during the test period. Measurements were performed at corresponding sites on both sides of the face 3 h after product application. Measurements were performed according to commonly used non-invasive bioengineering methods [26]. All participants provided informed consent prior to participation. The study was conducted in accordance with Regulation (EC) No 1223/2009 of the European Parliament and of the Council, the Cosmetics Europe guidelines on human skin compatibility testing and cosmetic efficacy evaluation, and the principles of the Declaration of Helsinki.

2.5.1. Skin Hydration

Skin hydration was measured using a Corneometer CM 825 (Courage + Khazaka electronic GmbH, Ehrenfeld, Germany). Measurements were performed before application and after 15, 60, and 120 min. The results were expressed in arbitrary units (a.u.). Each measurement was performed repeatedly at the same site, and extreme values were excluded before calculating the mean.

2.5.2. Transepidermal Water Loss

Transepidermal water loss was measured using a Tewameter TM 300 probe (Courage + Khazaka electronic GmbH, Germany). The measurement procedure and time points were identical to those used for the hydration test. Results were expressed as $\text{g}/\text{m}^2/\text{h}$.

2.5.3. Skin Lubrication

Skin lubrication was measured using the Sebu Pen SP15 (Courage + Khazaka electronic GmbH, Germany). The measurements were taken 3 h after applying the cosmetics. The effect of the formulation on skin surface lipid levels and its mattifying effect was assessed based on the percentage difference between the test and control groups.

2.6. Optical Measurements of Skin

2.6.1. Skin Color

Skin color was measured using a CR-400 colorimeter (Konica Minolta, Japan). Measurements were performed on marked 5×5 cm areas of the forearm before and 5 min after application of the emulsions. Results are expressed as L^* , a^* , and b^* values in the CIE $L^*a^*b^*$ color space. Each area was measured three times, and the mean value was used for analysis.

2.6.2. Skin Gloss

Skin gloss was measured using a ZGM 1120 glossmeter (Zehntner, Sissach, Switzerland). Measurements were performed at angles of 20° , 60° , and 85° , with the 60° angle used for final interpretation. Test areas were prepared on the forearm to imitate dry and oily skin conditions. Dry skin conditions were obtained by wiping the area with an ethanol-based disinfectant, while oily skin conditions were obtained by applying fractionated coconut oil. Gloss was measured before and 5 min after emulsion application. Results were expressed in Gloss Units (GU).

2.7. Consumer Evaluation of the Sensory Appeal

Consumer evaluation of the sensory appeal was performed using a consumer panel consisting of 30 women aged 19–30 years, regularly using cosmetic emulsions such as face creams and body lotions. The samples were placed in identical glass containers coded with random symbols. Samples were evaluated in randomized order. The assessors evaluated the samples under laboratory conditions at room temperature and daylight.

The following product attributes were assessed: color, odor, cushion effect, homogeneity, consistency, and adhesion. After application to the dorsal side of the hand, the following post-application attributes were evaluated: spreadability, stickiness, greasiness, absorption, and smoothing effect. Each parameter was rated using a 5-point hedonic scale, where 1 indicated the least favorable and 5 the most favorable sensory perception. This scale is commonly applied in sensory studies [27]. The survey began with a statement regarding informed consent to participate. Respondents were free to withdraw their consent to continue participating at any time, without giving a reason. Respondents were informed that the data collected for the purposes of the survey would not contain any personal data (e.g., name, address, national insurance number). The collected data is stored in a secure location, accessible only to the study authors. The scope of the study complies with Regulation (EC) No 1223/2009 of the European Parliament and of the Council, the guidelines of Cosmetics Europe-The Personal Care Association “Product Test Guidelines for the Assessment of Human Skin Compatibility 1997”, Cosmetics Europe-The Personal Care Association’s “Guidelines for the Evaluation of the Efficacy of Cosmetic Products 2008”,

and the World Medical Association (WMA) Declaration of Helsinki on ethical principles in medical research involving human subjects.

2.8. Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics 26 (IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated for all measured parameters and are presented as mean values $\pm$ standard deviation (SD).

The effect of orange peel microparticle concentration on the evaluated parameters was assessed using analysis of variance (ANOVA). Depending on the experimental design, between-subject and mixed-model ANOVA approaches were applied. When statistically significant effects were detected, post hoc multiple comparison tests were performed using Tukey's test or Games–Howell test, depending on the homogeneity of variances.

For skin hydration and transepidermal water loss measurements, changes over time and differences between formulations were evaluated using repeated measurements obtained from the same participants. For all analyses, statistical significance was established at $\alpha = 0.05$ ($p < 0.05$).

All measurements were performed at least in triplicate unless otherwise stated.

3. Results and Discussion

3.1. Physicochemical Properties of Emulsions

The physicochemical properties of the developed emulsions were evaluated in terms of viscosity, pH, and color parameters (CIELab system). The results are presented in Figures 1–5.

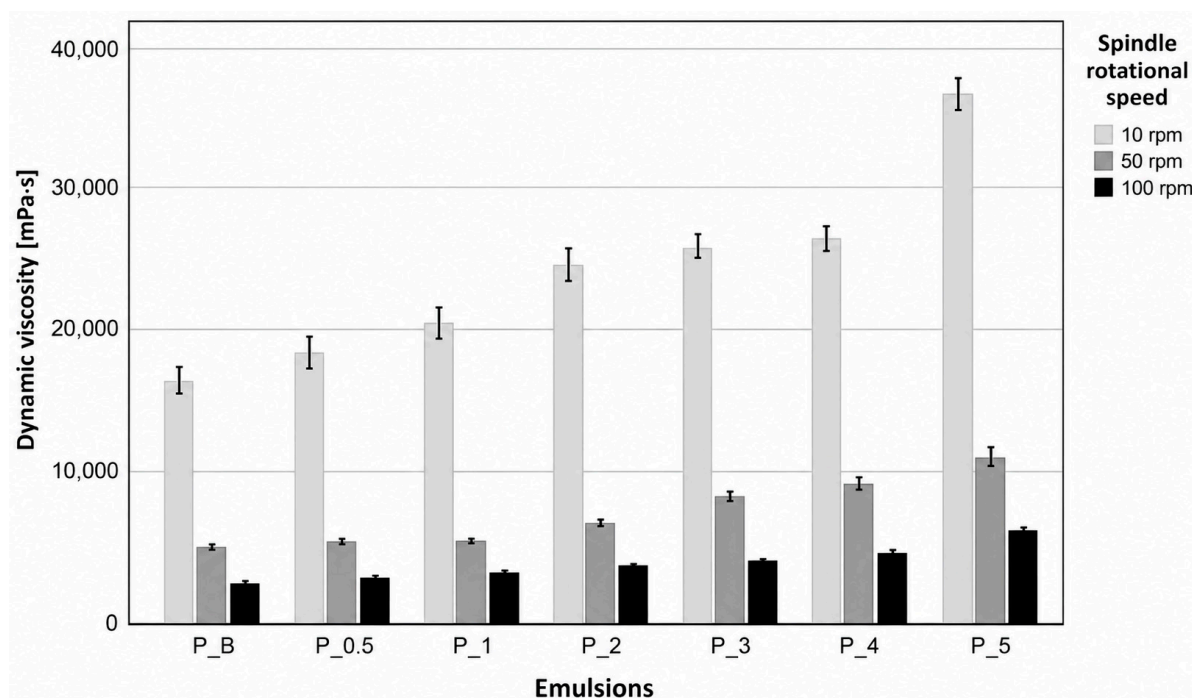


Figure 1. Mean dynamic viscosity of emulsion formulations as a function of orange peel microparticle concentration in the samples, measured at spindle rotational speeds of 10, 50, and 100 rpm.

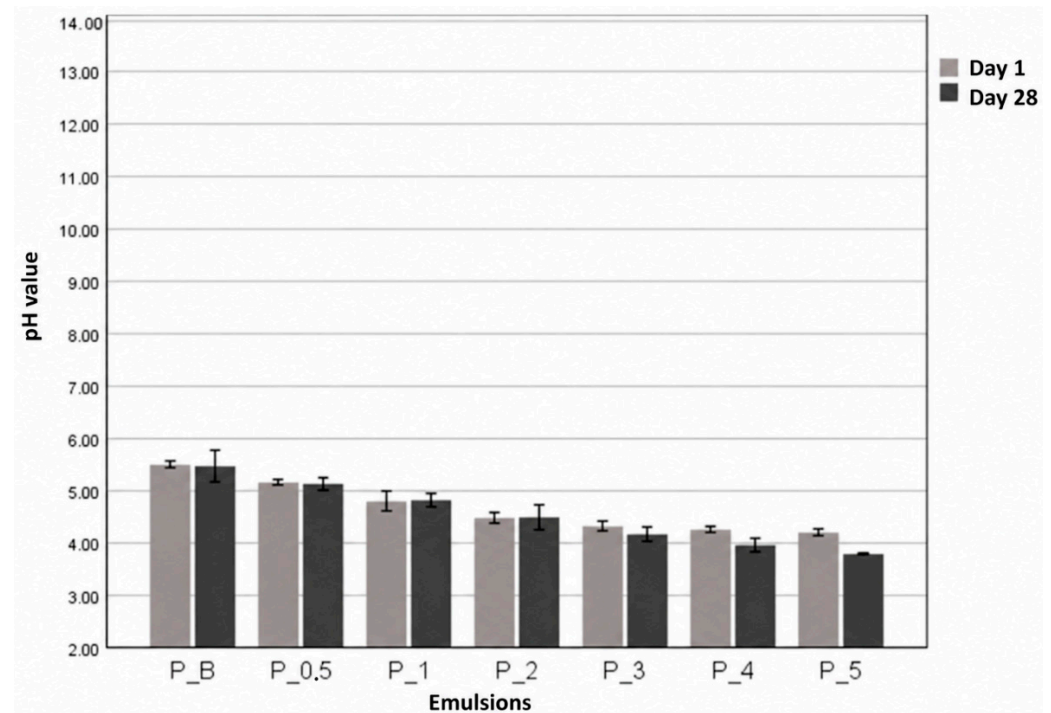


Figure 2. Mean pH of emulsion formulations as a function of orange peel microparticle concentration in the samples (full scale).

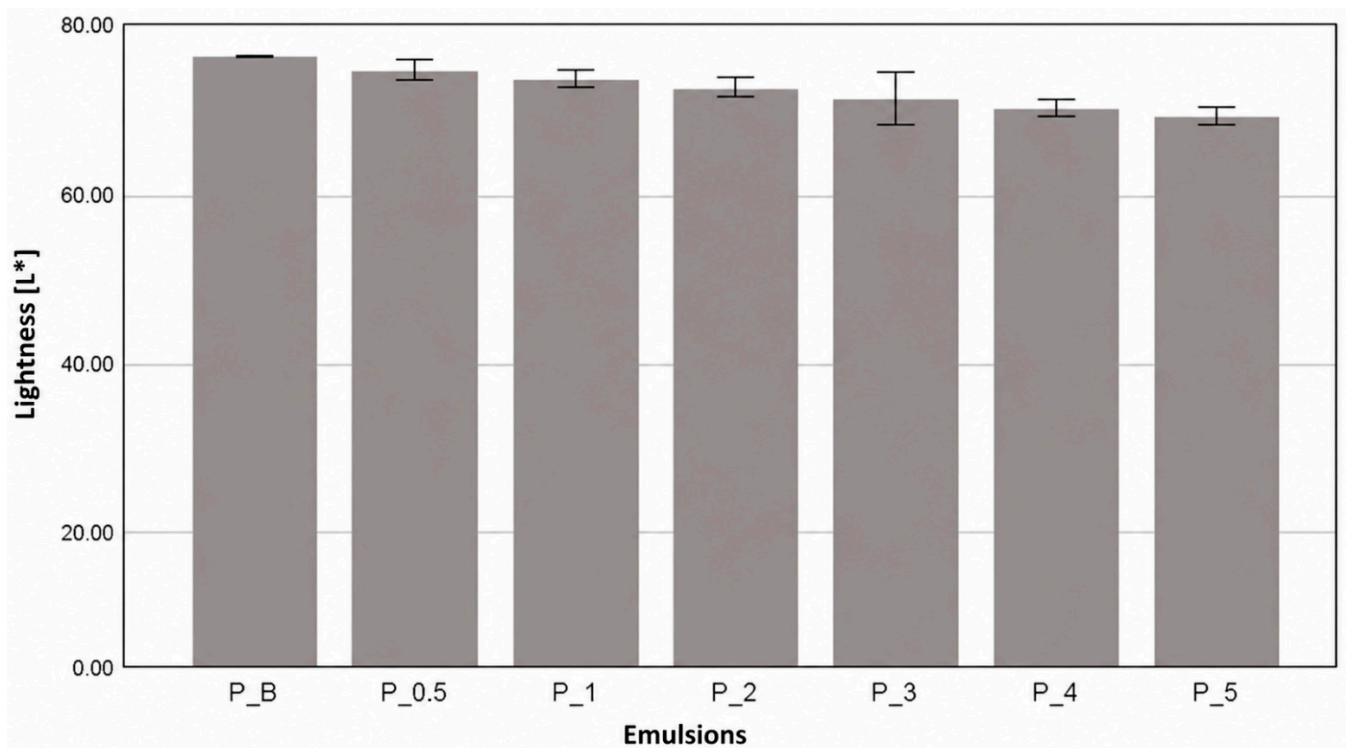


Figure 3. Mean lightness of emulsion formulations as a function of orange peel microparticle concentration in the samples.

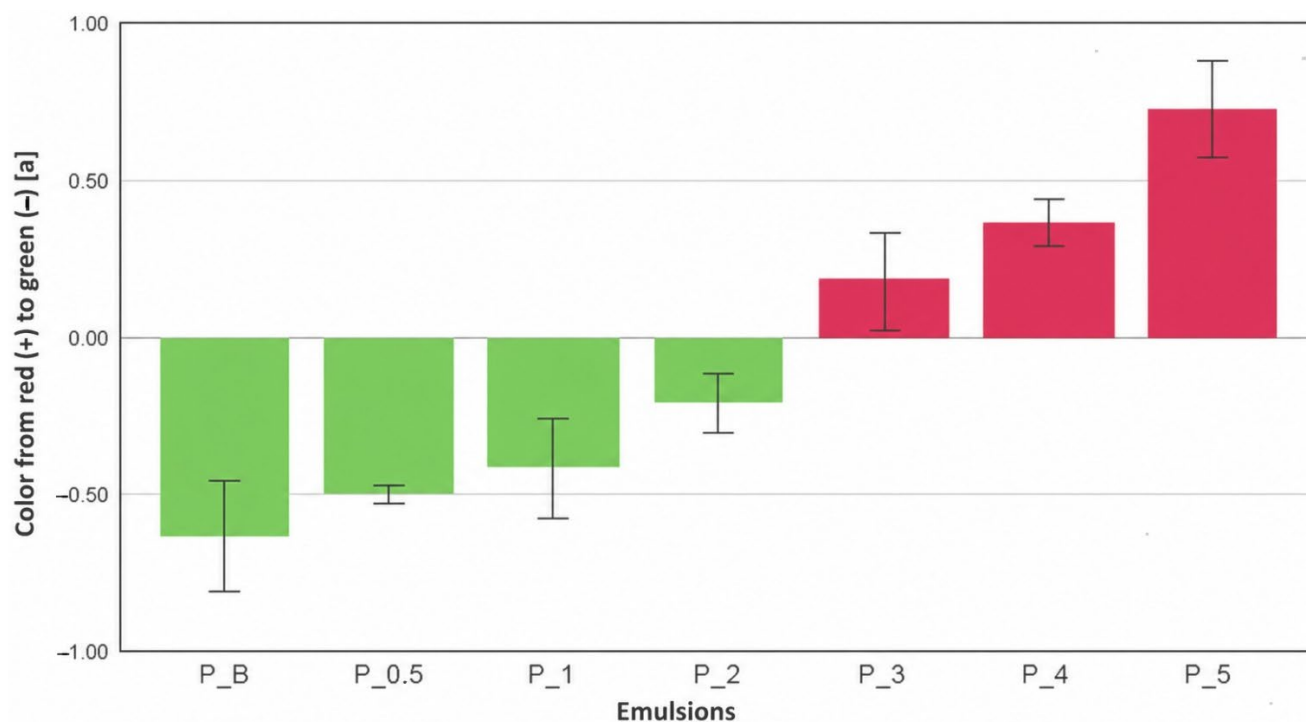


Figure 4. Mean a^* parameter of emulsion formulations as a function of orange peel microparticle concentration in the samples.

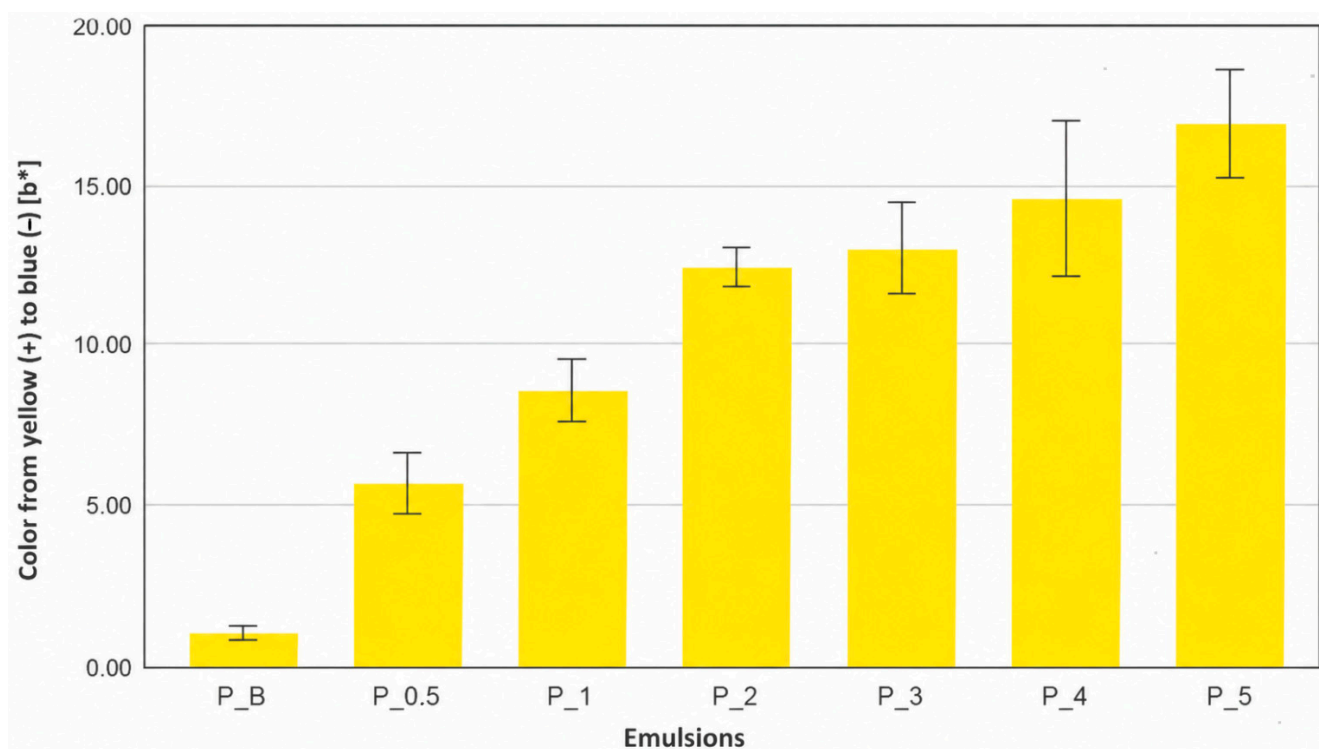


Figure 5. Mean b^* parameter of emulsion formulations as a function of orange peel microparticle concentration in the samples.

3.1.1. Viscosity

A statistically significant effect of microparticle concentration on the viscosity of the emulsions was observed. The results of dynamic viscosity measurements (Figure 1) showed significant differences between most samples, except for formulations containing 0.5% and 1% microparticles at 50 rpm, where no statistically significant differences were found.

The viscosity of all formulations decreased with increasing shear rate, indicating shear-thinning behavior typical for cosmetic emulsions. At the same time, an increase in microparticle concentration resulted in an increase in viscosity, confirming the structuring effect of the dispersed solid phase.

Viscosity increased from approximately 17,000 mPa·s for the base formulation (0%) to approximately 36,000 mPa·s for the formulation containing 5% microparticles.

The observed increase in viscosity can be attributed to the swelling ability of plant microparticles and the increase in their specific surface area, which enhances interactions within the continuous phase. Similar viscosity-enhancing effects after incorporation of plant-derived particles into emulsion systems were also reported by Muiz et al. [28], who observed that by-product-derived Pickering particles increased emulsion viscosity and resistance to creaming due to intensified particle interactions within the continuous phase. Although the systems investigated by Muiz et al. were particle-stabilized emulsions, the reported rheological effects remain relevant because they reflect general mechanisms associated with the presence of dispersed plant particles within emulsion systems. Comparable concentration-dependent rheological changes were described in cellulose-based emulsions, where increasing particle content strengthened the internal structure and significantly modified flow behavior [29].

Based on the obtained results, the 2–4% range provided favorable viscosity and application-related properties; however, considering the overall balance between stability, sensory performance, and functional effects, 2% was considered the most practically suitable concentration.

3.1.2. pH

The analysis of pH values revealed a statistically significant effect of microparticle concentration on the acidity of the emulsions (Figure 2).

As presented in Figure 2, the incorporation of orange peel microparticles significantly affected the pH of the developed emulsions. The base formulation (P_B) exhibited a pH value of approximately 5.5, while increasing concentrations of microparticles resulted in a gradual decrease in pH. The most pronounced changes were observed between the control sample and formulations containing up to 2% microparticles. Above this concentration, the differences in pH became less pronounced and were no longer statistically significant.

The trend observed in Figure 2 suggests that the acidity of the final formulations was influenced by the intrinsic properties of the orange peel material. The gradual decrease in pH may be associated with the presence of naturally occurring organic acids and phenolic compounds in citrus by-products. Similar effects have been reported by Chakraborty et al. [30], who observed pH reduction after the incorporation of orange-derived materials into emulsion systems.

Importantly, despite the statistically significant differences observed between formulations, all pH values remained within the physiologically acceptable range for topical application. As shown in Figure 2, none of the tested formulations exceeded the pH range generally considered suitable for cosmetic products intended for skin contact.

3.1.3. Color (CIELab Parameters)

Colorimetric analysis showed that the incorporation of plant microparticles significantly affected the visual properties of the emulsions.

Figures 3–5 present the effect of orange peel microparticle concentration on the color parameters of the developed emulsions. As shown in Figure 3, increasing microparticle concentration resulted in a progressive decrease in the L^* value, indicating gradual darkening of the formulations. The lowest lightness values were observed for emulsions

containing the highest concentrations of microparticles, confirming the visible influence of the plant-derived material on the appearance of the products.

In contrast, Figure 4 demonstrates only minor changes in the a^* parameter across the tested formulations, indicating a limited contribution of red color components. Although slight increases in a^* values were observed with increasing microparticle concentration, these changes were considerably less pronounced than those observed for the other color parameters.

The most significant effect was observed for the b^* parameter (Figure 5). As the concentration of orange peel microparticles increased, the b^* value also increased, indicating a progressively stronger contribution of yellow tones to the overall color of the emulsions. This trend is consistent with the natural pigmentation of orange peel and may be associated with the presence of carotenoids and other colored compounds occurring in citrus by-products [31].

Taken together, the results presented in Figures 3–5 clearly demonstrate that even relatively small changes in microparticle concentration affected the visual characteristics of the emulsions. Statistical analysis confirmed significant differences between formulations, indicating that orange peel microparticles may act not only as functional ingredients but also as natural modifiers of product appearance.

Total color difference (ΔE)

In addition to individual CIELab parameters, the total color difference (ΔE) between formulations was calculated based on L^* , a^* , and b^* values. The averaged results are presented as a matrix.

The total color differences (ΔE) calculated between the formulations are presented in Table 2. The data clearly demonstrate that the magnitude of color differences increased with increasing differences in microparticle concentration between the compared samples.

Table 2. Total color difference between emulsion formulations as a function of orange peel microparticle concentration in the samples.

	P _B	P _{0.5}	P ₁	P ₂	P ₃	P ₄	P ₅
P _B		5.18 ± 0.28	8.30 ± 0.37	12.02 ± 0.34	13.54 ± 0.84	15.23 ± 0.78	17.69 ± 0.72
P _{0.5}	5.18 ± 0.28		3.20 ± 0.35	6.90 ± 0.21	8.48 ± 0.78	10.12 ± 0.67	12.59 ± 0.94
P ₁	8.30 ± 0.37	3.20 ± 0.35		3.74 ± 0.13	5.32 ± 0.52	7.07 ± 0.29	9.50 ± 1.03
P ₂	12.02 ± 0.34	6.90 ± 0.21	3.74 ± 0.13		1.74 ± 0.63	3.59 ± 0.25	5.91 ± 1.04
P ₃	13.54 ± 0.84	8.48 ± 0.78	5.32 ± 0.52	1.74 ± 0.63		2.15 ± 0.58	4.33 ± 1.47
P ₄	15.23 ± 0.78	10.12 ± 0.67	7.07 ± 0.29	3.59 ± 0.25	2.15 ± 0.58		2.21 ± 1.37
P ₅	17.69 ± 0.72	12.59 ± 0.94	9.50 ± 1.03	5.91 ± 1.04	4.33 ± 1.47	2.21 ± 1.37	

As shown in Table 2, the smallest color differences were observed between formulations with similar microparticle contents, particularly between P₂ and P₃ ($\Delta E = 1.74 \pm 0.63$), P₃ and P₄ ($\Delta E = 2.15 \pm 0.58$), and P₄ and P₅ ($\Delta E = 2.21 \pm 1.37$). In contrast, the largest differences were recorded between the base formulation (P_B) and samples containing the highest concentrations of orange peel microparticles. The greatest ΔE value was observed between P_B and P₅ ($\Delta E = 17.69 \pm 0.72$), indicating a substantial visual difference between these formulations.

The results presented in Table 2 are consistent with the trends observed for the individual CIELab parameters shown in Figures 3–5. The progressive decrease in L^* values and increase in b^* values contributed to increasingly pronounced color differences as the concentration of orange peel microparticles increased.

Overall, the ΔE analysis confirms that orange peel microparticles significantly influenced the visual appearance of the emulsions. The results indicate that the plant-derived material may contribute not only to the functional properties of the formulations but also to their color characteristics, acting as a natural color-modifying ingredient.

3.2. Stability

The physicochemical stability of the developed emulsions was evaluated using multiple light scattering analysis (Turbiscan), based on the measurement of backscattered light intensity as a function of sample height.

The stability profiles of the developed emulsions obtained by multiple light scattering analysis are presented in Figures 6–12. The results indicate that the concentration of orange peel microparticles influenced the internal organization and long-term stability of the emulsion systems.

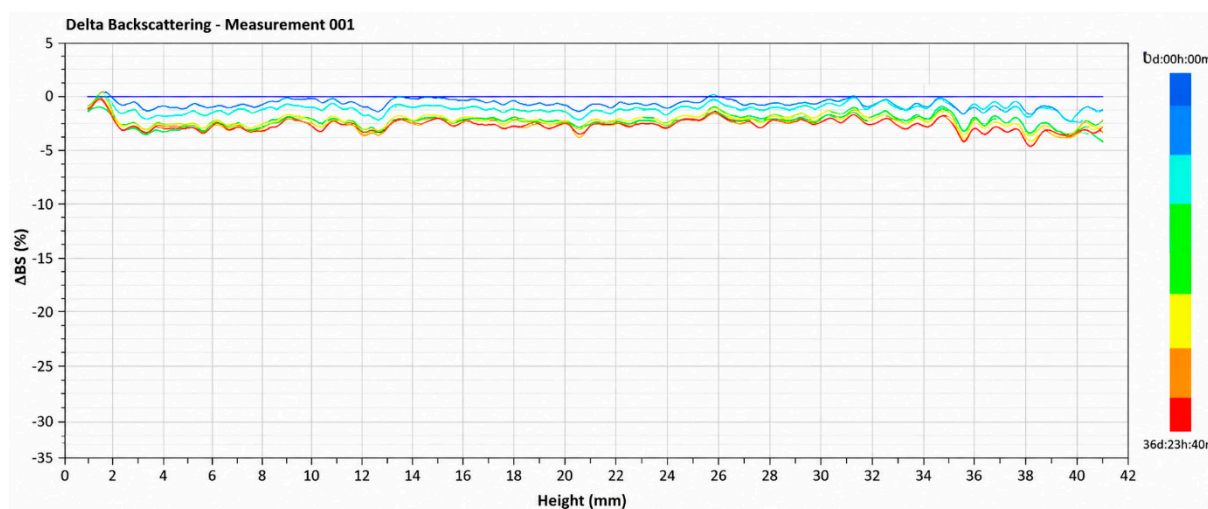


Figure 6. Delta backscattered light (backscattering) for the base sample (P_B) without microparticle content.

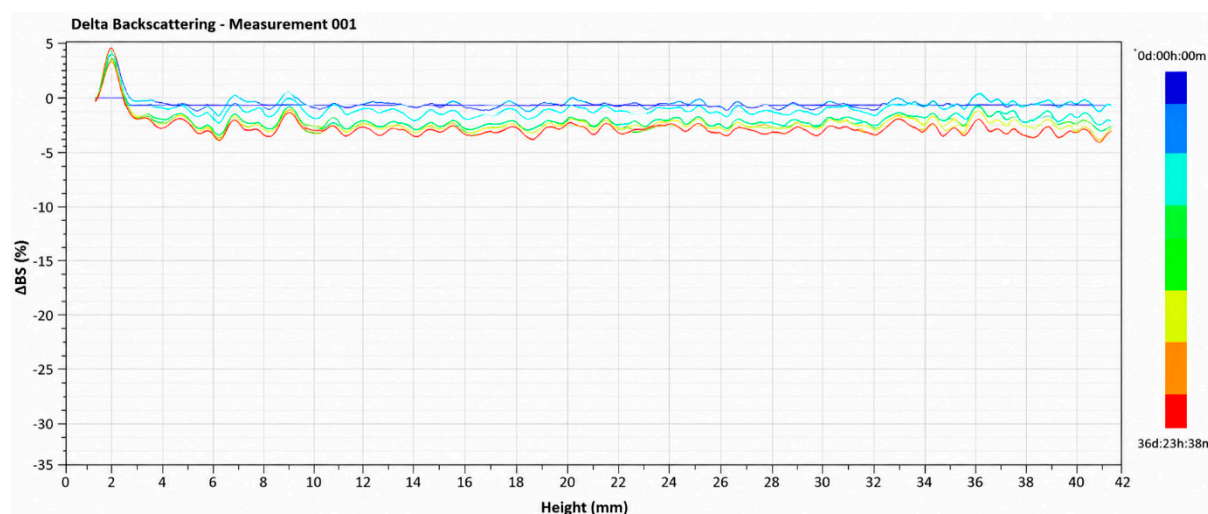


Figure 7. Delta backscattered light (backscattering) for sample P_0.5.

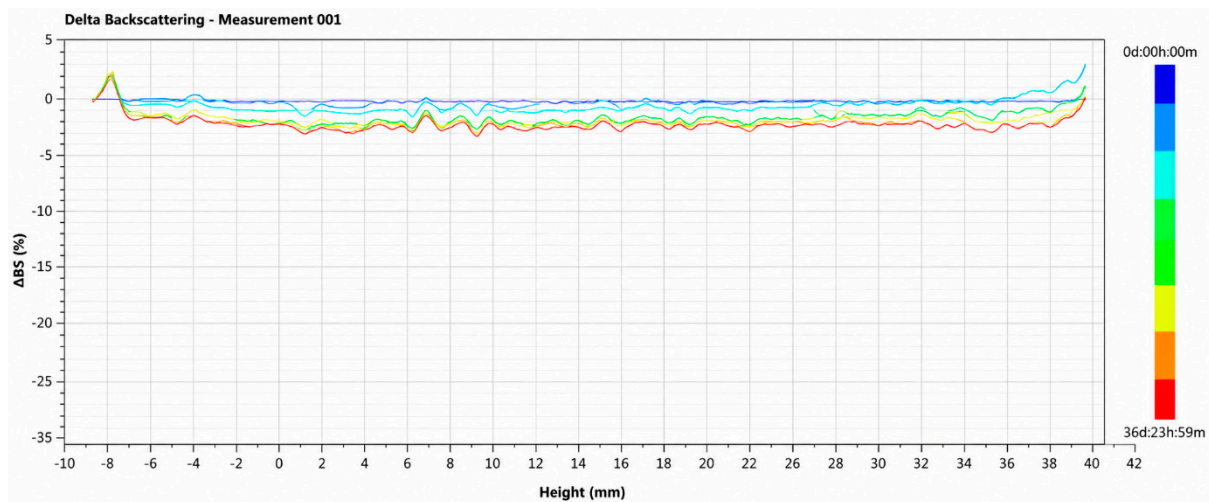


Figure 8. Delta backscattered light (backscattering) for sample P_1.

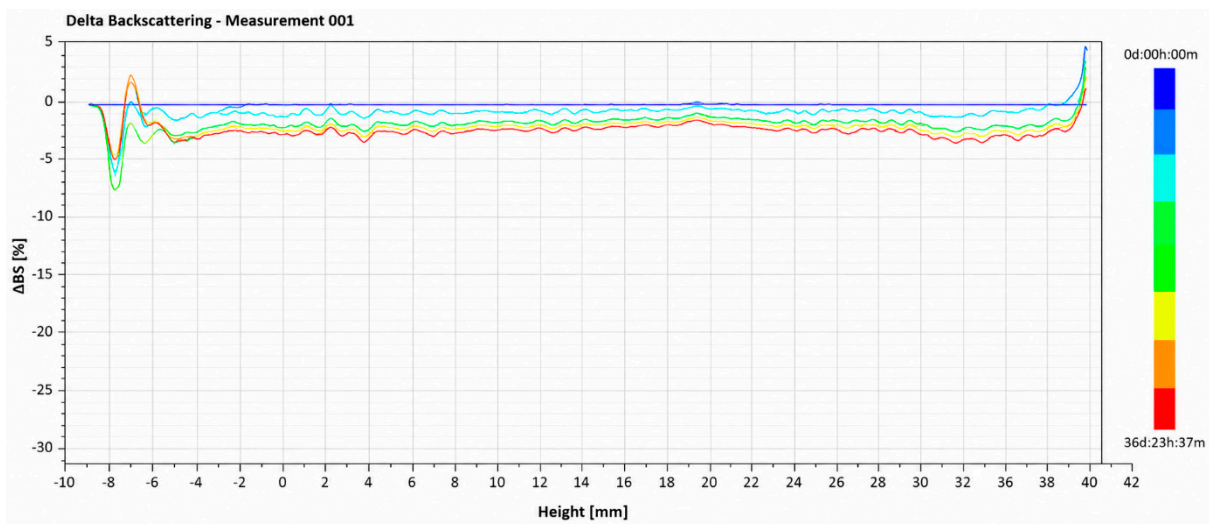


Figure 9. Delta backscattered light (backscattering) for sample P_2.

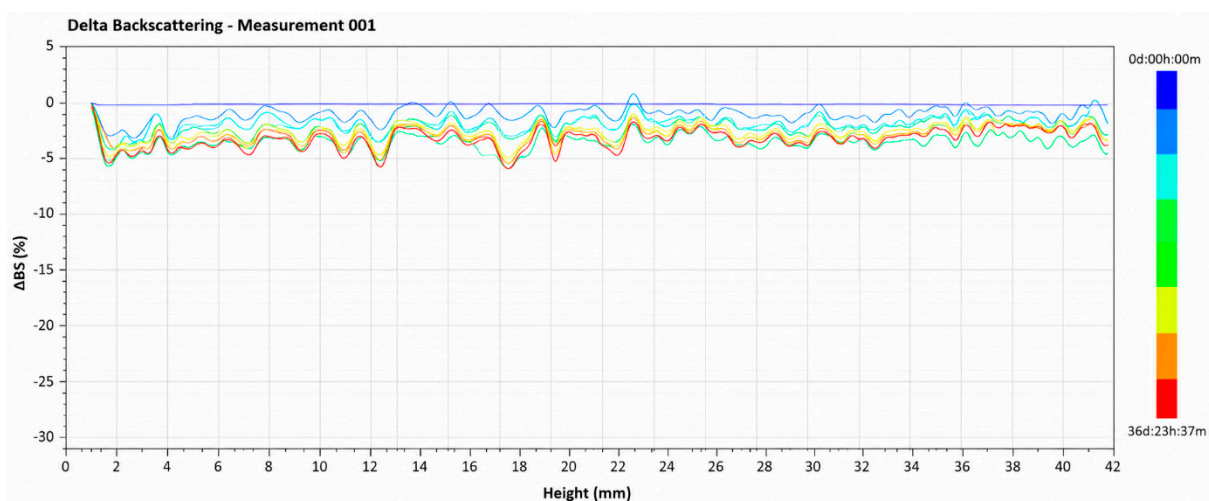


Figure 10. Delta backscattered light (backscattering) for sample P_3.

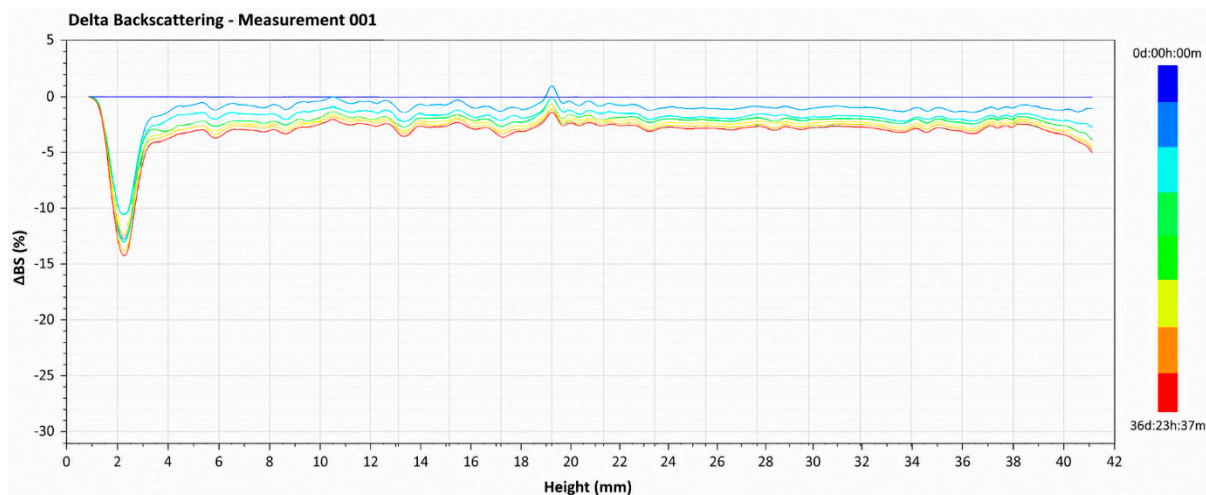


Figure 11. Delta backscattered light (backscattering) for sample P_4.

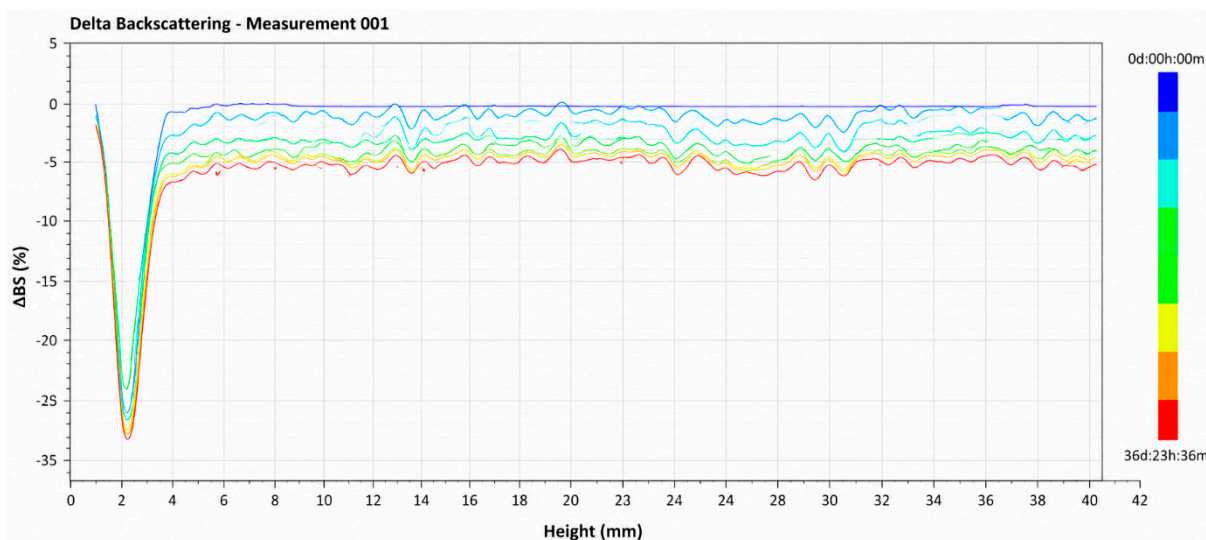


Figure 12. Delta backscattered light (backscattering) for sample P_5.

As shown in Figures 6–9, corresponding to the base formulation (P_B) and formulations containing 0.5%, 1%, and 2% microparticles, only minor changes in backscattering intensity were observed throughout the storage period. The relatively stable backscattering profiles across the sample height indicate that no significant destabilization processes, such as creaming, sedimentation, or coalescence, occurred in these systems.

In contrast, Figures 10–12 demonstrate that formulations containing higher concentrations of orange peel microparticles (3–5%) exhibited more pronounced variations in backscattering intensity. These changes were particularly visible in specific regions of the sample height, suggesting local structural rearrangements within the emulsions. The magnitude of these variations increased with increasing microparticle concentration, indicating a greater tendency toward instability at higher particle loadings.

The trends observed in Figures 6–12 suggest that the increased amount of dispersed solid material enhanced particle–particle interactions within the emulsion structure. Similar observations were reported by Huc-Mathis et al. [32], who demonstrated that micronized orange pomace can effectively stabilize emulsions, although excessive particle concentrations may adversely affect system stability. While the formulations investigated in the present study were not Pickering emulsions, these reports provide useful mechanistic insight into how increasing concentrations of plant-derived particles may affect emulsion

organization and stability. Comparable conclusions were also presented by Sarkar and Dickinson [18], who emphasized that the stabilizing performance of plant-derived particles strongly depends on their concentration, aggregation state, and interactions within the continuous phase.

Although Figures 10–12 reveal a greater degree of structural change compared with the lower-concentration formulations, none of the analyzed samples showed complete phase separation during the test period. This indicates that the applied emulsifying system maintained the overall structural integrity of all formulations. Based on the stability profiles presented in Figures 6–12, formulations containing up to 2% orange peel microparticles provided the most favorable balance between physical stability and potential functional benefits.

3.3. Antioxidant Activity (DPPH)

The antioxidant activity of the emulsion systems was evaluated using the DPPH radical scavenging assay, based exclusively on the results obtained for the emulsions containing different concentrations of orange peel microparticles.

The antioxidant activity of the developed emulsions, determined using the DPPH radical scavenging assay, is presented in Figure 13. The results demonstrate a clear concentration-dependent increase in antioxidant activity with increasing orange peel microparticle content.

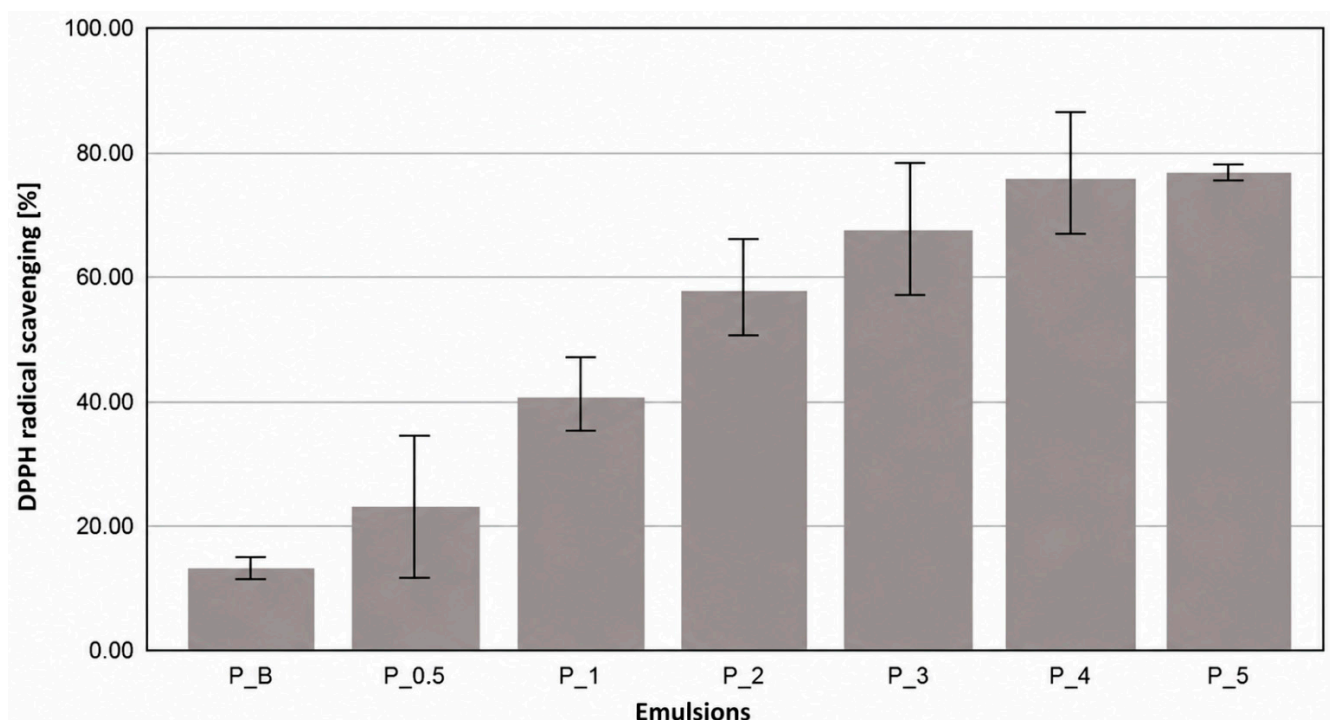


Figure 13. Mean percentage of DPPH radical scavenging by emulsion formulations as a function of orange peel microparticle concentration in the samples.

As shown in Figure 13, the base emulsion (P_B) exhibited the lowest antioxidant activity, whereas formulations containing orange peel microparticles displayed progressively higher DPPH radical scavenging capacity. The increase was particularly pronounced between the control formulation and emulsions containing 2–5% microparticles. The highest antioxidant activity was observed for formulations P_5 and P_4, which achieved approximately 77% and 76% DPPH inhibition, respectively.

The data presented in Figure 13 indicate that the antioxidant potential of the emulsions was directly related to the concentration of orange peel microparticles incorporated into the formulation. This trend suggests that the plant-derived material acted as an effective source of antioxidant compounds and retained its biological activity within the emulsion matrix.

The observed results are consistent with previous studies. Castro-Vázquez et al. [33] reported that orange peel by-products are rich in flavonoids and phenolic compounds, including hesperidin and narirutin, which contribute significantly to antioxidant activity. Similarly, Adeel et al. [34] demonstrated high antioxidant activity in cosmetic emulsions containing fruit-derived materials. The role of particulate systems as carriers of antioxidant compounds was also highlighted by Keramat et al. [35], who reported improved antioxidant performance in particle-stabilized emulsion systems.

Overall, Figure 13 clearly demonstrates that increasing the concentration of orange peel microparticles substantially enhanced the antioxidant properties of the developed emulsions. The results confirm that these plant-derived particles may provide both structural functionality and biologically relevant antioxidant activity within cosmetic formulations.

3.4. Skin Biophysical Parameters

3.4.1. Skin Hydration

The effect of orange peel microparticles on skin hydration is presented in Figure 14. Skin hydration was measured before application and after 15, 60, and 120 min following the application of emulsions containing different concentrations of microparticles.

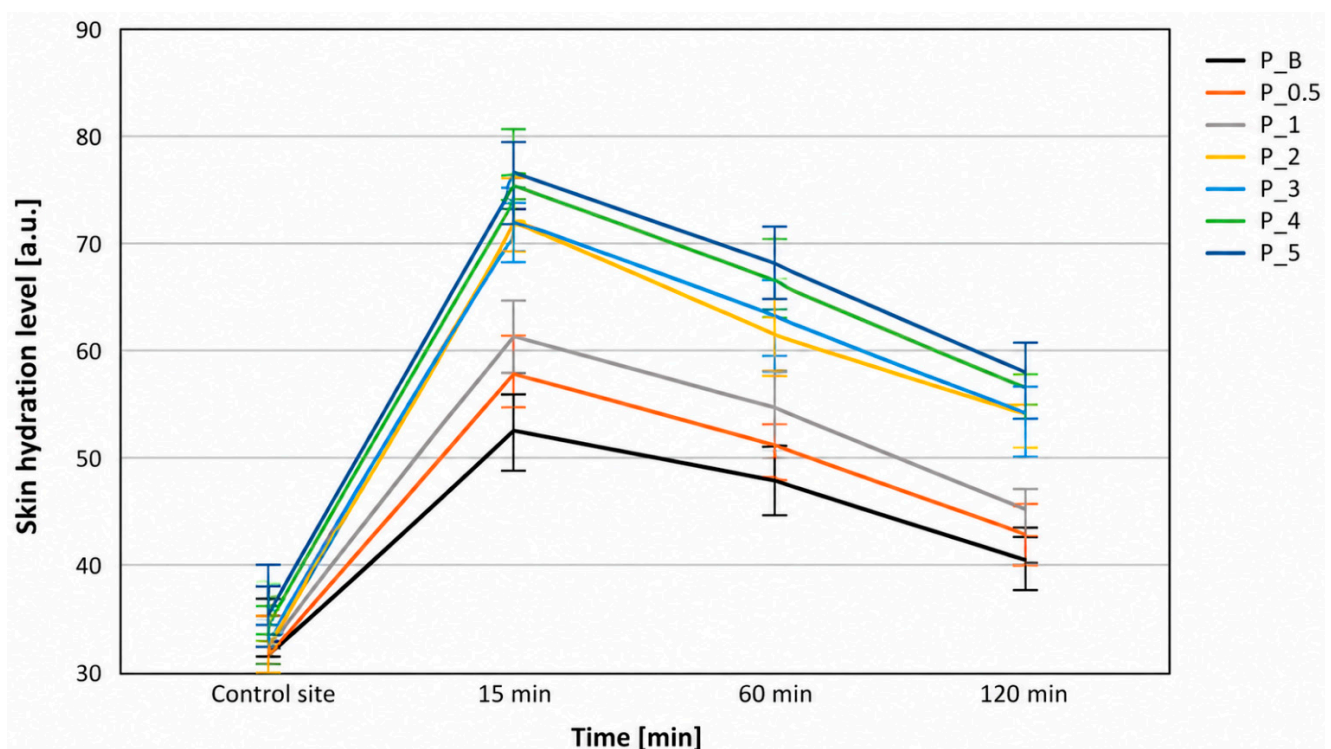


Figure 14. Mean skin hydration before emulsion application (control site) and at 15, 60, and 120 min after application as a function of orange peel microparticle concentration in the samples.

As shown in Figure 14, all tested formulations increased the hydration level of the stratum corneum over time. However, the magnitude of this effect depended on microparticle concentration. The base emulsion (P_B) produced the smallest increase in skin hydration, with values rising from approximately 33.7 a.u. before application to approximately 40.4 a.u. after 120 min, corresponding to an increase of about 7%.

Figure 14 further demonstrates a concentration-dependent improvement in hydration performance following the incorporation of orange peel microparticles. Formulations containing higher concentrations of microparticles consistently produced greater increases in hydration at all measurement time points. The strongest effect was observed for formulations P_4 and P_5, which showed no statistically significant differences from each other. For formulation P_5, hydration increased from approximately 37 a.u. before application to approximately 57 a.u. after 120 min, corresponding to an increase of approximately 54%.

The results presented in Figure 14 suggest that the plant-derived microparticles contributed to improved water retention within the stratum corneum. Similar hydration-enhancing effects of plant-derived polysaccharides and bioactive compounds have been reported by Yao and Xu [36], who demonstrated that natural biopolymers may support skin hydration through moisture-binding and film-forming mechanisms.

Importantly, the baseline hydration values measured before treatment were generally within the range of 30–40 a.u., corresponding to dry skin conditions. As shown in Figure 14, formulations containing medium and high concentrations of orange peel microparticles increased hydration values to approximately 50–60 a.u. after 120 min, indicating a substantial improvement in skin moisturization and a transition toward adequately hydrated skin.

3.4.2. Transepidermal Water Loss—TEWL

The effect of the developed emulsions on transepidermal water loss (TEWL) is presented in Figure 15. Measurements were performed before application and after 15, 60, and 120 min to evaluate changes in skin barrier function over time.

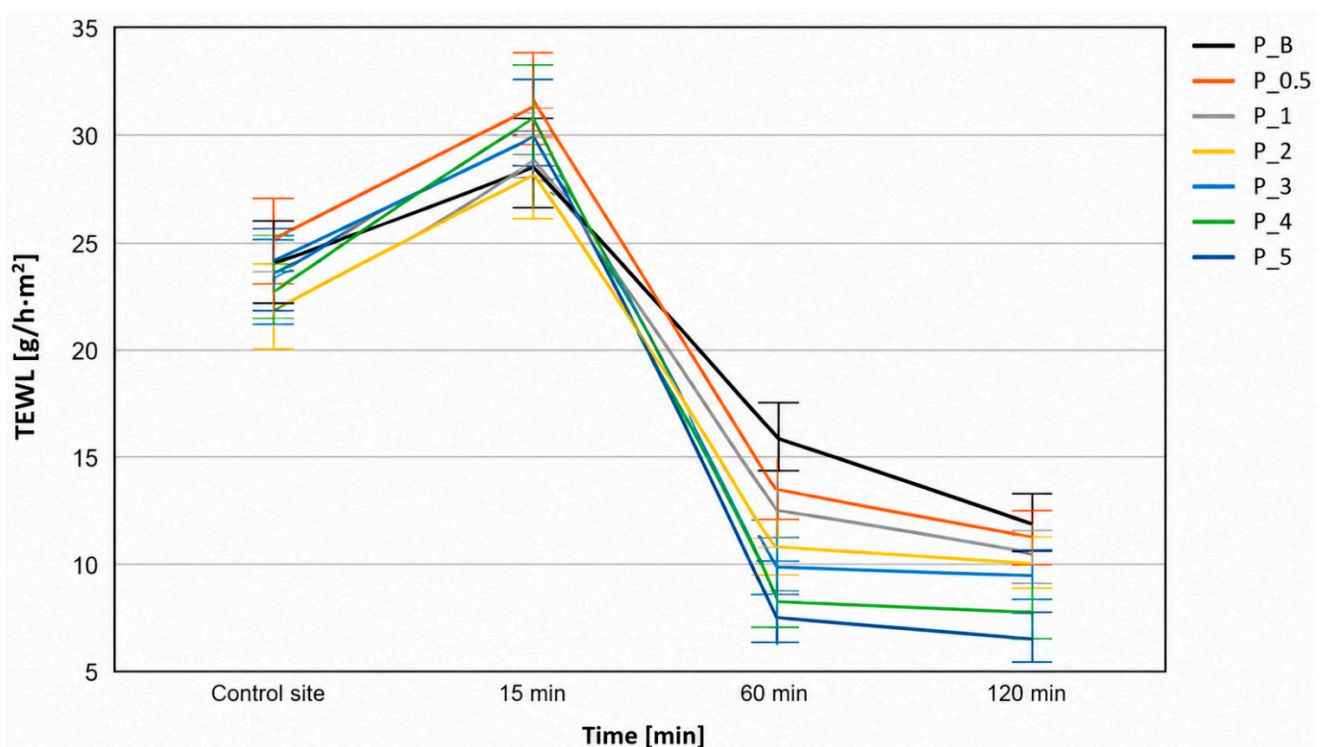


Figure 15. Mean TEWL values before emulsion application (control site) and at 15, 60, and 120 min after application as a function of orange peel microparticle concentration in the samples.

As shown in Figure 15, all formulations exhibited a similar general trend. Shortly after application, TEWL values increased compared with baseline measurements. This initial increase can be attributed to the evaporation of water from the freshly applied emulsion. However, with increasing time after application, TEWL values gradually de-

creased, indicating improved water retention and the formation of a protective layer on the skin surface.

The extent of TEWL reduction depended on the concentration of orange peel microparticles. It should be noted that the relatively high baseline TEWL values observed in this study may have been influenced by seasonal factors, as the measurements were performed during the winter heating season, when reduced ambient humidity may adversely affect skin barrier function. Figure 15 demonstrates that the base formulation (P_B) produced the weakest effect, reducing TEWL from approximately 24 g/m²/h before application to approximately 12 g/m²/h after 120 min, corresponding to a reduction of about 50%. In contrast, formulations containing higher concentrations of microparticles provided substantially greater reductions in TEWL.

The strongest effect was observed for formulation P_5. As shown in Figure 15, TEWL decreased from approximately 24 g/m²/h before application to approximately 6 g/m²/h after 120 min, corresponding to an approximately fourfold reduction. Similar trends were observed for formulation P_4, indicating that higher microparticle concentrations were associated with enhanced barrier-supporting effects.

Statistical analysis revealed significant differences between the base formulation and formulations containing higher concentrations of orange peel microparticles, particularly P_4 and P_5. According to the data presented in Figure 15, formulations containing medium and high concentrations of microparticles reduced TEWL values to approximately 5–10 g/m²/h after 120 min, indicating a substantial improvement in skin barrier function compared with baseline conditions.

The results suggest that orange peel microparticles may contribute to improved water retention within the stratum corneum, thereby supporting the barrier properties of the skin. Overall, Figure 15 demonstrates a clear concentration-dependent relationship between microparticle content and TEWL reduction.

3.4.3. Skin Lubrication and Mattifying Effect

Based on the research results (Figure 16) obtained, it was unequivocally concluded that the application of cosmetic emulsions to the facial skin, with an increasing proportion of orange peel microparticles in the formulations, leads to a reduction in skin lubrication across all skin types. Furthermore, when emulsion P_5, containing 5% orange peel microparticles, was applied to the facial skin, a mattifying effect was observed. It was also found that significant changes compared to the control area were noted after applying an emulsion containing more than 1% orange peel microparticles to the face. In all skin types (dry, normal, and combination/oily), the effect of orange peel microparticles on facial lubrication is observed. No significant differences in the measured parameter were observed for the emulsion containing more than 1% orange peel microparticles.

Choudhry et al. [37] developed an emulsion containing an extract from the galls of *Quercus infectoria* Olivier and examined its effect on the mechanical properties of the skin and its anti-aging properties. The study reported an increase in sebum levels on the facial skin. However, in this case, it was observed in both the control emulsion and the test emulsion, in contrast to the results presented in this article. This increase may result from the presence of an oil phase in both the control emulsion and the test emulsion. In contrast, Ogorzałek et al. demonstrated in their study [38] that the use of cosmetic oils based on natural and synthetic emollients leads to an increase in skin lipid content. However, a smaller decrease in the level of skin lubrication was observed after the application of body oils based on natural emollients.

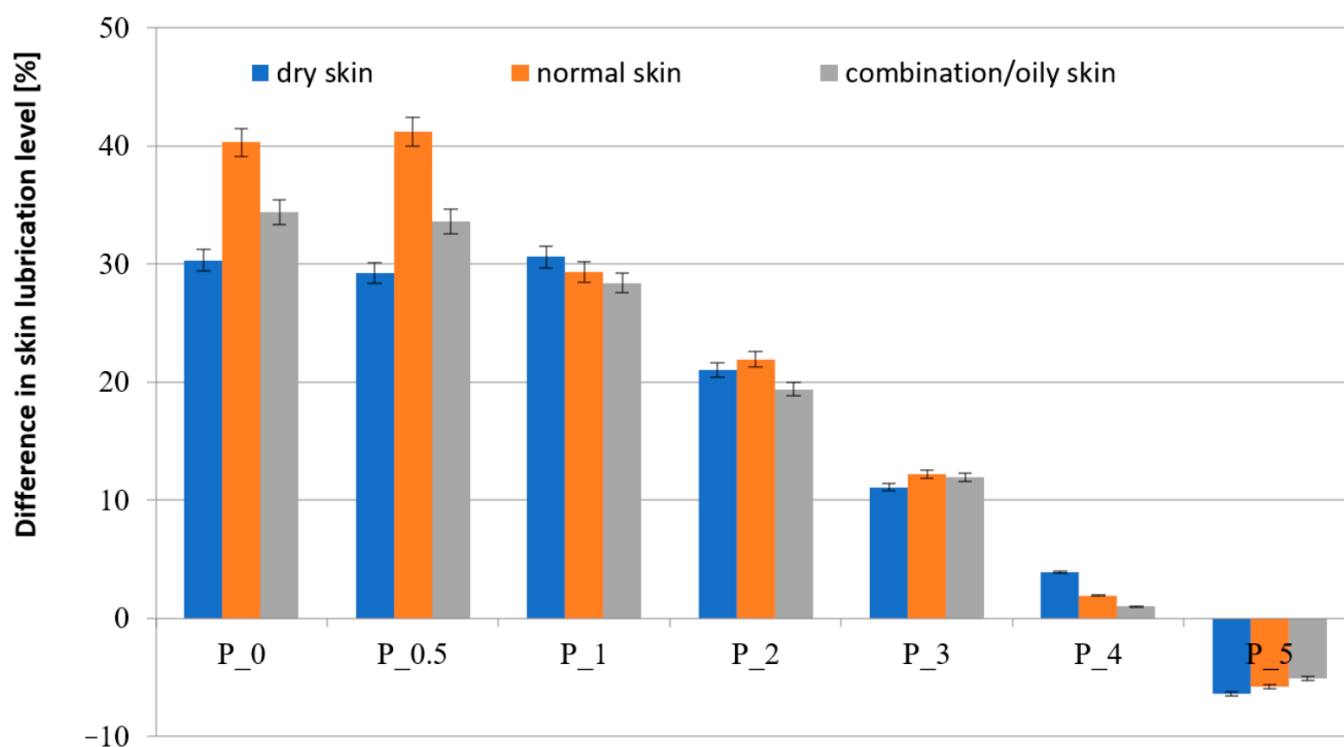


Figure 16. Difference in skin lubrication level after applying the emulsion as a function of the concentration of orange peel microparticles.

3.5. Immediate Optical Effects

3.5.1. Skin Color

The immediate effect of the developed emulsions on skin color was evaluated by comparing the total color difference (ΔE) before and after product application. The results are presented in Figure 17.

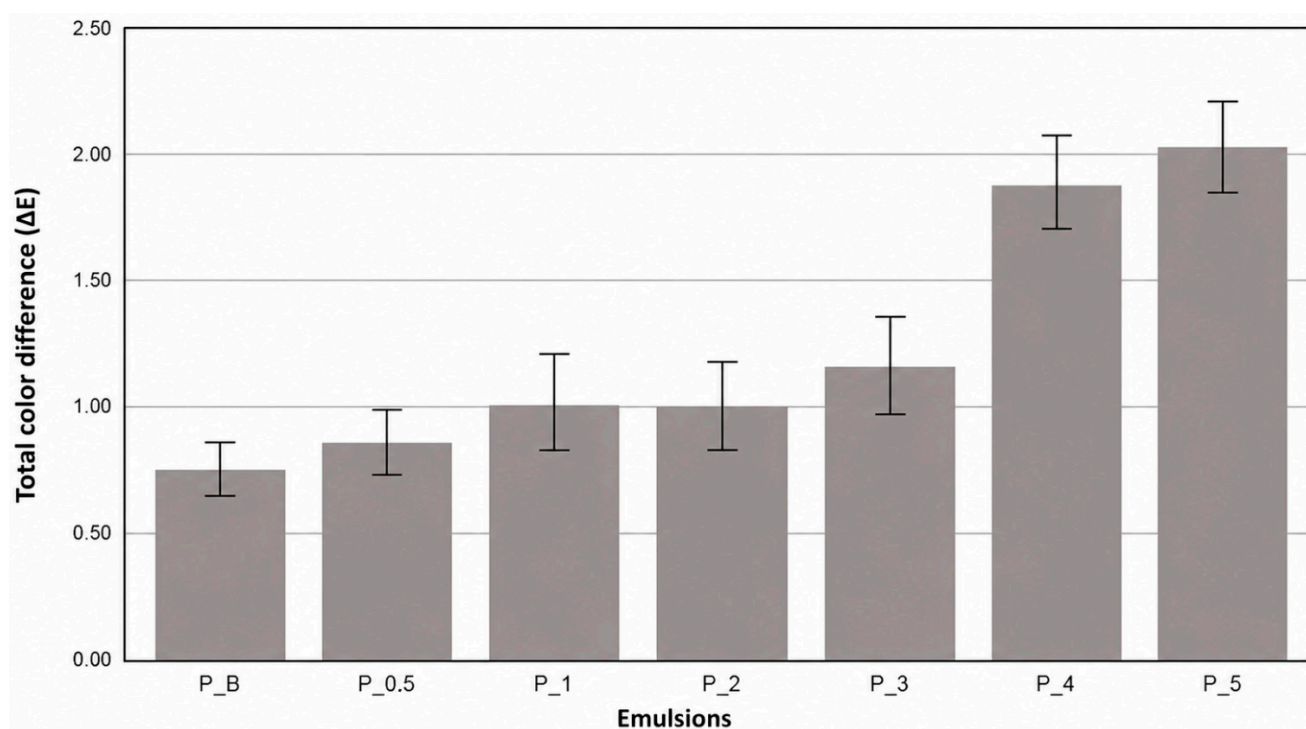


Figure 17. Total color difference in the skin before and after emulsion application as a function of orange peel microparticle concentration in the samples.

As shown in Figure 17, the magnitude of skin color change increased with increasing concentration of orange peel microparticles in the formulations. The base emulsion (P_B) produced the smallest color difference, with a ΔE value of approximately 0.73, whereas the formulation containing 5% microparticles (P_5) exhibited the highest value, reaching approximately $\Delta E = 2.03$.

Figure 17 further demonstrates a concentration-dependent trend, with progressively higher ΔE values observed as the concentration of orange peel microparticles increased. Statistical analysis revealed significant differences between the base formulation and emulsions containing 3%, 4%, and 5% microparticles, indicating that higher concentrations of the plant-derived material exerted a measurable influence on the optical appearance of the skin immediately after application. The observed differences are most likely related to the increasing deposition of orange peel microparticles and naturally occurring pigments on the skin surface as their concentration in the formulation increased. At lower concentrations (0.5–2%), the amount of deposited material was insufficient to induce measurable changes in skin color. However, at concentrations of 3% and above, the cumulative contribution of carotenoids, flavonoids, and colored plant particles became more pronounced, resulting in statistically significant increases in ΔE values. The concentration-dependent character of this effect is consistent with the progressive increase in b^* values observed for the formulations themselves, indicating a stronger contribution of yellow color tones originating from the orange peel material.

The observed changes may be attributed to the natural pigments present in orange peel as well as the deposition of microparticles on the skin surface. Similar effects have been reported for cosmetic formulations containing plant-derived pigments and fruit-processing by-products, where natural particles modified skin appearance without producing pronounced or long-lasting staining effects [39].

Despite the statistically significant differences observed in Figure 17, the practical visual impact remained limited. The ΔE values obtained for all formulations remained relatively low, suggesting that the color changes would be imperceptible or only slightly perceptible under normal use conditions. Therefore, the incorporation of orange peel microparticles did not result in an intense or cosmetically undesirable coloration of the skin.

3.5.2. Skin Gloss

The influence of orange peel microparticles on skin gloss is presented in Figure 18. The measurements were performed separately on experimentally prepared dry and oily skin models to evaluate the immediate optical effects of the tested formulations.

As shown in Figure 18, the effect of the emulsions on skin gloss depended strongly on the initial condition of the skin. For dry skin, all formulations increased gloss after application, although the magnitude of the increase varied according to microparticle concentration. The greatest increase in gloss was observed for the base formulation (P_B) and formulation P_0.5, both of which increased gloss by approximately 52%. In contrast, the formulation containing 5% microparticles (P_5) produced the smallest increase, reaching only approximately 5%.

The results presented in Figure 18 suggest that formulations with lower concentrations of microparticles were more effective in enhancing the visual radiance of dry skin. This effect may be associated with the formation of a smooth reflective film on the skin surface, which contributes to a healthier and less dull appearance.

In contrast, an opposite trend was observed for oily skin. As shown in Figure 18, increasing concentrations of orange peel microparticles resulted in progressively greater reductions in skin gloss. The strongest mattifying effect was recorded for formulation P_5,

which reduced gloss by approximately 31%, whereas the base formulation reduced gloss by only approximately 2%.

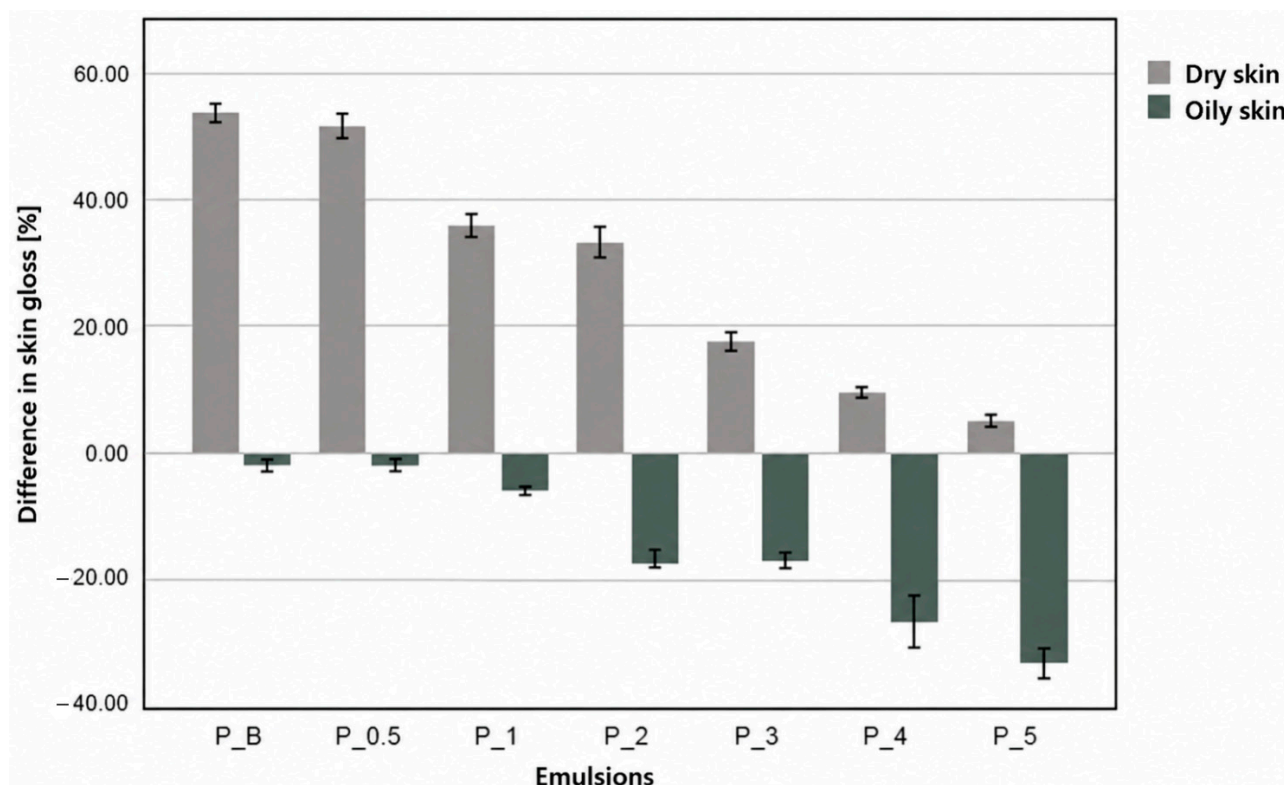


Figure 18. Total percentage difference in skin gloss (dry and oily skin) before and after emulsion application as a function of orange peel microparticle concentration in the samples.

These results indicate that orange peel microparticles can effectively modify the optical appearance of the skin depending on the formulation concentration. Lower concentrations may be more suitable for improving the appearance of dry skin, whereas higher concentrations may provide a desirable mattifying effect for oily skin. Similar reductions in skin gloss have been reported for cosmetic formulations containing plant-derived powders with high oil-absorption capacity, where adsorption of surface lipids contributed to decreased skin shine [40].

Overall, Figure 18 demonstrates that orange peel microparticles exert a concentration-dependent effect on skin gloss. While their influence on skin color remained relatively subtle, their effect on gloss was more pronounced and may be of practical relevance for tailoring cosmetic formulations to different skin types.

3.6. Consumer Evaluation of the Sensory Appeal

The sensory appeal of the emulsions developed was assessed by consumers as part of an organoleptic study conducted by a panel of 30 women aged 19–30. The assessment covered parameters relating to both application properties and post-application effects on the skin, which were presented in the form of two separate sensory profiles.

3.6.1. Properties of the Emulsions Before and During Application

The first sensory profile concerned parameters assessed before and during application, including color, intrinsic odor, cushion effect, uniformity, consistency and adhesion. The results showed a clear influence of microparticle concentration on all assessed attributes. In their responses, the respondents rated the formulations containing 4% (P_4) and 5% (P_5) orange peel microparticles most highly, taking into account the following parameters:

intrinsic odor, cushion effect, uniformity and adhesion. In terms of color, the highest scores were awarded to formulations P_2 and P_3, respectively. The consistency parameter, however, was rated highest for emulsions P_2 and P_5, both receiving a score of 4.8. Furthermore, the highest adhesion was recorded for the formulation containing 4% and 5% microparticles, confirming the optimal concentration for application performance. It should be noted that respondents rated the application properties of emulsions P_4 and P_5 highly, in contrast to the results for the color parameter, where these samples received the lowest scores. Similar improvements in spreadability, reduction in stickiness, and enhancement of overall sensory perception after incorporation of plant-derived particles into cosmetic formulations were reported by Wasilewski et al. [41], who demonstrated that solid particles obtained from plant materials may beneficially modify the rheological and application properties of cosmetic emulsions. The overall sensory profiles of the tested formulations are presented in Figure 19.

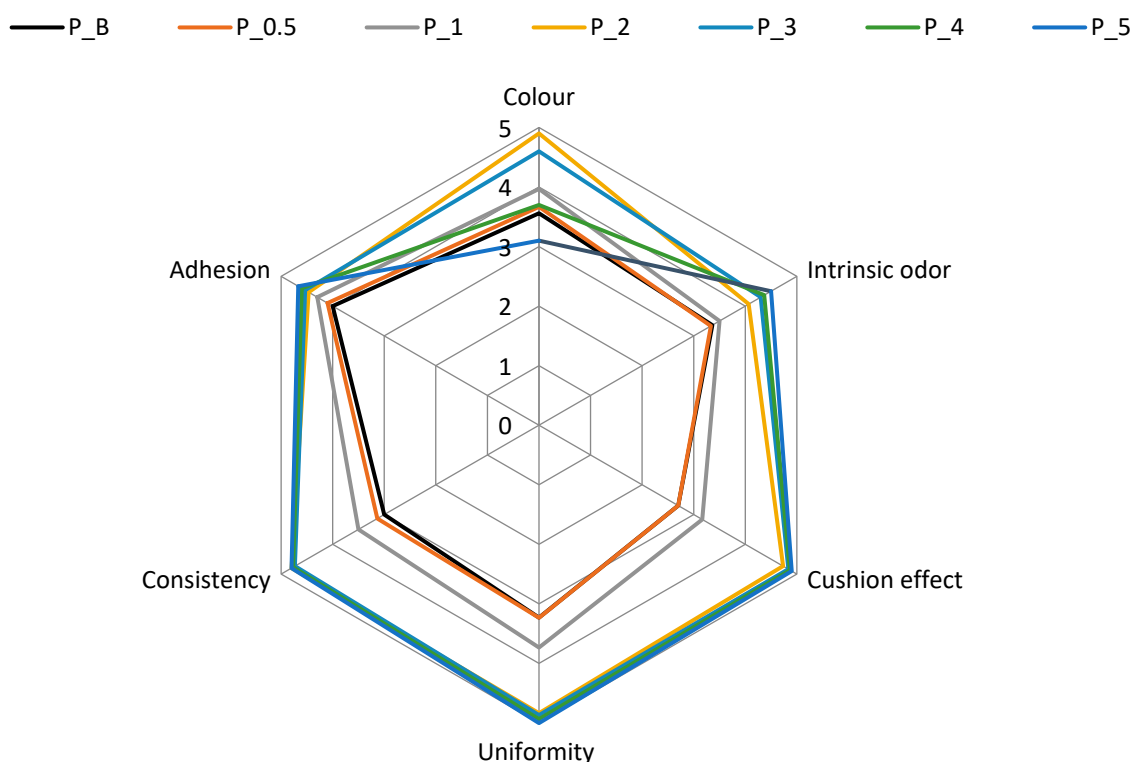


Figure 19. Sensory profile of emulsion formulations as a function of orange peel microparticle concentration in the samples.

3.6.2. Post-Application Skin Effects

The second sensory profile covered parameters assessed after application, such as spreadability, stickiness, greasiness, absorption and smoothing effect.

The results indicated that, following application of the tested emulsions containing microparticles, respondents gave significantly higher ratings compared to the base formulation for all the parameters in question. Respondents awarded the highest scores to formulations with the highest microparticle content (3–5%). Taking into account all parameters assessed after application, the highest score was recorded for emulsion P_5. Comparable sensory benefits of plant-derived solid particles in topical formulations were also reported by Wasilewski et al. [41], who demonstrated that incorporation of plant-based particles may improve spreadability, skin feel, and overall application properties of cosmetic formulations. The sensory profiles of post-application skin effects are presented in Figure 20.

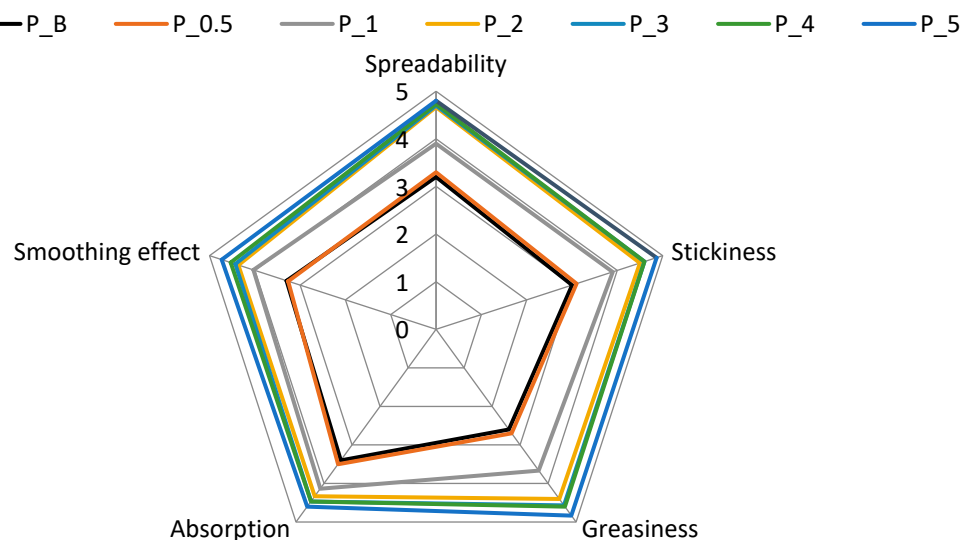


Figure 20. Sensory profile of post-application effects on the skin of emulsion formulations as a function of orange peel microparticle concentration in the samples.

The sensory evaluation confirmed a statistically significant improvement in both application properties and post-application skin effects with increasing microparticle concentration up to an optimal level (2–3%). Beyond this range, further improvements were not observed for all parameters, indicating a concentration-dependent effect of plant-derived microparticles on sensory performance.

Beyond the observed effects on sensory properties, the results obtained in this study suggest that orange peel microparticles may offer considerable practical value for cosmetic formulation development. The material acted as a multifunctional ingredient, simultaneously affecting viscosity, antioxidant activity, skin hydration, transepidermal water loss, skin lubrication, and sensory characteristics. Such multifunctionality is particularly attractive from a formulation perspective, as it may reduce the number of separate ingredients required to achieve multiple product claims and technological functions. In addition, orange peel represents a widely available agro-industrial by-product generated in large quantities worldwide, making it an economically attractive raw material for cosmetic applications. Its utilization is consistent with current industry trends focused on circular economy principles, upcycling strategies, and the replacement of synthetic microplastic-based materials with renewable alternatives. The results indicate that concentrations between 2% and 4% may be particularly promising, providing a favorable balance between formulation stability, sensory acceptance, and functional performance. At the same time, the reduced stability observed at the highest concentrations highlights the importance of optimizing particle content for practical applications. From an industrial perspective, the incorporation of orange peel microparticles could provide an opportunity to develop products with both sustainability-related and performance-related marketing claims. Nevertheless, additional studies evaluating long-term storage stability, compatibility with different formulation types, large-scale production processes, and consumer acceptance under real-use conditions are required before full commercial implementation can be recommended.

4. Conclusions

The present study demonstrated a clear concentration-dependent effect of orange peel microparticles (0–5%) on the properties of cosmetic emulsions. Increasing microparticle content resulted in a significant rise in viscosity from approximately 17,000 mPa·s (0%) to approximately 36,000 mPa·s (5%), confirming their structuring effect within the emulsion system. At the same time, antioxidant activity increased markedly from approximately

13% DPPH scavenging in the base formulation to approximately 77% at 5%, indicating nearly a sixfold increase in radical scavenging capacity. Changes in color parameters (L^* , a^* , b^*) confirmed progressive darkening of the formulations with increasing microparticle concentration, reflected in increasing ΔE values.

Although statistically significant changes in pH were observed with increasing microparticle concentration, all formulations remained within the physiologically acceptable range for topical application, confirming the compatibility of orange peel microparticles with the emulsion system.

In terms of skin-related effects, the base formulation increased skin hydration from approximately 33.7 a.u. to 40.4 a.u. after 120 min (approximately 7% increase), whereas formulations containing higher concentrations of microparticles showed a substantially stronger effect. The highest increase was observed for the 5% formulation, where hydration increased from approximately 37 a.u. to approximately 57 a.u. (approximately 54% increase), indicating a marked improvement in skin moisturization. At the same time, the initial hydration level of the skin (30–40 a.u., corresponding to dry skin) increased to 50–60 a.u. after application, indicating a transition to adequately hydrated skin.

Analysis of TEWL showed a characteristic trend, with an initial increase shortly after application (due to water evaporation), followed by a reduction over time, which can be attributed to the formation of a semi-occlusive film on the skin surface and improved water retention associated with the presence of plant-derived microparticles. Increasing microparticle concentration was also associated with a reduction in skin surface lubrication, contributing to a concentration-dependent mattifying effect. In addition, the optical measurements demonstrated that orange peel microparticles could modify the visual appearance of the skin, providing either enhanced radiance or a more pronounced mattifying effect depending on the formulation concentration.

Although formulations containing 4–5% orange peel microparticles showed the highest antioxidant activity, strongest skin-related effects, and favorable sensory performance, they also exhibited reduced physical stability and more pronounced changes in formulation appearance. Therefore, the 2% formulation was considered the most suitable overall concentration, as it provided a compromise between physical stability, functional efficacy, acceptable sensory performance, and practical formulation robustness. Higher concentrations (≥ 3 –5%) further enhanced antioxidant activity and hydration but resulted in excessive viscosity and reduced application comfort.

The obtained results indicate that orange peel microparticles can act as multifunctional cosmetic ingredients, provide rheological modification, antioxidant activity, and measurable skin benefits, while enabling the development of sustainable formulations based on upcycled plant-derived raw materials.

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Institutional Review Board Statement: This study was approved by the Bioethics Committee of the Casimir Pulaski University of Radom (Project title: “Influence of active substances on physicochemical and usable properties of selected cosmetic products used in various disease entities”; Approval code: Resolution No. KB/04/2024; Date of approval: 14 May 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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