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A Dual ZnO Dispersion Strategy for Viscosity Control and Long-Term Stability in Sun-screens

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1. Introduction

Zinc oxide (ZnO)-based mineral sunscreens have become increasingly favored in UV protection applications for their safety profile, natural origin, broad-spectrum efficacy, skin compatibility and regulatory approval across global markets. Compared with titanium dioxide, ZnO offers broader-spectrum protection within a narrower particle size range and results in minimal white cast, making it well-suited for use in mineral sunscreens across diverse skin tones. It stays on top of the skin to absorb, reflect, and scatter UV radiation, minimizing systemic absorption and risks of irritation associated with organic UV filters.

Beyond UV protection, ZnO offers dermatological benefits such as anti-bacterial, non-comedogenic properties, and anti-inflammatory effects, making it an ideal choice for sensitive and acne-prone skin [1-5]. As consumer demand for 'clean' and environmentally conscious beauty continues to grow, formulating sunscreens with natural mineral UV filters, particularly ZnO alone, has emerged as a key focus for the global personal care industry.

Oil-in-water (O/W) and water-in-oil (W/O) emulsions are the most widely used formats for mineral sunscreens, offering advantages in cost-effectiveness, formula flexibility, and sensory experience. However, incorporating high loadings of ZnO presents considerable difficulties [6]. In O/W emulsions, dispersing ZnO in the discontinuous oil phase complicates its stabilization and uniform distribution, affecting both product stability and even skin application. This often leads to formula instability, poor spreadability, and uneven UV coverage, especially at higher ZnO concentrations. Although O/W systems are strongly preferred by consumers due to their light, refreshing sensory, achieving high SPF values with ZnO-only formulas in this format is notoriously difficult [7]. Maintaining low viscosity and pleasant aesthetics simultaneously also proves challenging, particularly given the limited availability of natural thickeners.

Meanwhile, W/O emulsions offer a technical advantage by suspending ZnO in the continuous oil phase, which promotes better distribution and more efficient UV protection (typically 1–1.5 SPF units per 1% ZnO). W/O systems can achieve SPF values up to 50 with 25% ZnO, whereas O/W systems achieve approximately SPF 37.5 at this level. However, stabilizing high

ZnO loadings (up to 25%) in W/O while maintaining a light, moisturizing feel also demands considerable formulation effort.

Moreover, natural ZnO-based emulsions have historically been challenged by undesired viscosity increase over time, a phenomenon widely attributed to Zn ion migration. This thickening behavior directly translates into a poor consumer experience with a heavy, greasy feel and poor spreadability, potentially discouraging sunscreen use. Despite efforts to modify ZnO surface chemistry using natural treatments, consistent viscosity and pH stability remain difficult to achieve, as highlighted later in the Discussion. There remains a substantial gap in the literature for robust methods that stabilize both viscosity and pH in low-viscosity mineral sunscreen systems.

Addressing these key obstacles, this work develops practical, high-load ZnO formulas with enhanced natural content. The research targets improved stability, sensory properties, and UV protection while aligning with evolving beauty standards and regulatory compliance. This study also addresses the critical need to achieve high SPF performance with a >99.5% natural origin content (NOC), representing a significant milestone for clean-label mineral sunscreens.

While identifying a single formula effective across diverse ZnO dispersions remains a substantial challenge, this study provided valuable insights. Preliminary results successfully explored the stability boundaries in O/W systems, indicating instability at 100% uncoated ZnO (uZnO) concentration in this formula. This finding strategically led the viscosity investigation to prioritize W/O systems, enabling a clearer understanding of dispersion behavior under more stable conditions. The O/W findings are nonetheless still highly valuable for their groundbreaking achievement of serum-like viscosity, offering crucial insights into formulation thresholds and guiding future advancements.

Overall, this work demonstrates that a novel dual dispersion strategy significantly enhances both O/W and W/O emulsions. For O/W systems, it delivers a refreshing sensory profile, lower viscosity and improved pH stability. For W/O emulsions, the strategy achieves higher SPF performance, a moisturizing sensory with better aesthetics and superior viscosity control.

2. Materials and Methods

Pre-dispersed anhydrous ZnO systems were selected over powders to enhance consistency, minimize aggregation/agglomeration, ensure uniform particle size distribution, and improve handling. These dispersions promoted uniform ZnO distribution, improved formulation stability, and ensured reliable UV protection. Their use also allowed for isolation of surface treatment effects while eliminating variability associated with poor powder incorporation.

Three ZnO dispersions were selected for this study based on their natural origin content, long-term stability and commercial availability. These included two uZnO dispersions (ZD-1 and ZD-2, each with 100% NOC) and one triethoxycaprylylsilane-coated ZnO (TS-ZnO) dispersion (ZDC) with 98.4% NOC, as summarized in Table 1. Each dispersion had an average primary particle size of 30–35 nm and remained stable over a shelf life of three years. This further prevents the risk of ZnO aggregation or agglomeration, minimizes variability and allows the study to focus solely on in-formula dispersibility and stability.

Table 1. Summary of composition and ZnO content in selected dispersions.

Sample	**ZnO Content**	**INCI**
ZDC	78%	Zinc Oxide (and) Coco Caprylate/Caprate (and) Polyhydroxystearic Acid (and) Polyglyceryl-3 Polyricinoleate (and) Triethoxycaprylylsilane (and) Lecithin
ZD-1	70%	Zinc Oxide (and) Caprylic/Capric Triglyceride (and) Polyhydroxystearic Acid (and) Polyglyceryl-3 Polyricinoleate (and) Isostearic Acid (and) Lecithin
ZD-2	72%	Zinc Oxide (and) Coco Caprylate/Caprate (and) Polyhydroxystearic Acid (and) Lauroyl Lysine (and) Isostearic Acid

Formulation Development: Two emulsion systems —O/W and W/O — were developed to assess the effects of ZnO dispersion combinations on formula stability and performance. O/W emulsions (Formulas 1a–1c, Table 2) were prepared with 20.72% ZnO, while W/O emulsions (Formulas 2a–2b, Table 4) contained 24.50% ZnO.

Mixed dispersion systems were created by systematically varying the ratios of ZnO dispersions (70–78% ZnO; Tables 3 and Tables 5). The NOC was calculated for each formula, excluding preservative contribution. The oil phase was adjusted to maintain consistent oil-to-water ratios.

O/W emulsions (Formula 1) were prepared by heating the oil and water phases separately to 80°C, combining them under high shear, homogenizing for five minutes, cooling to 30°C, adding active ingredients, and adjusting the pH to ~ 7.

W/O emulsions were prepared entirely at room temperature (RT) by first adding the emulsifier to the oil phase, then combining it with the water phase under high shear, followed by five minutes of homogenization.

Stability Testing: The formulas were subjected to 3 freeze-thaw cycles, a one-month test at 50 °C, and a three-month test at RT to assess stability. During accelerated aging at 50°C, samples were cooled to RT weekly before viscosity (1 rpm, RT, Brookfield DV2T model) and pH were measured. Emulsion stability was observed and monitored by visual inspection and optical microscopy.

Sensory and SPF Testing: Sensory characteristics and SPF performance were evaluated through a small internal panel (n = 5) assessing spreadability, greasiness, and absorption. Selected O/W formulas were also tested in vivo (n = 3) for SPF following ISO 24444 guidelines.

Table 2. Base composition of O/W emulsions (Formulas 1a–1c) with ~83% NOC.

Phase	INCI Name	Formula 1a Wt%	Formula 1b Wt%	Formula 1c Wt%
Oil	ZDC	27.00	7.97-14.00	7.97-14.00
	ZD-1		14.00-20.72	
	ZD-2			13.61-20.14
	Isohexadecane	10.00	Q.S.	
	Butyloctyl Salicylate		5.00	
	Hydroxyethyl Acrylate/Sodium Acryloyldimethyl Taurate Copolymer (and) Water (and) C15-C23 Alkane (and) Decyl Glucoside (and) C13-C14 Alkane (and) Glycerin	3.00	3.00	
	Glyceryl Behenate	0.50	0.50	
	Polyglyceryl-10 Mono/Dioleate	3.00	3.00	
Water	Water	49.0	38.00	
	Preservative	0.50	1.00	
	Glycerin	1.00	3.00	
	Erythritol	3.00	3.00	
	Sorbitol	3.00	3.00	
Active	Biosaccharide Gum-1		1.00	
	Propanediol (and) Water (and) Piperonyle glucose		2.00	

Table 3. ZnO distribution (20.72% solid) and NOC calculation in O/W formulas 1b and 1c.

	OW-1	OW-2	OW-3	OW-4	OW-1b	OW-2b	OW-3b	OW-4b
Ratio	52/48	40/60	30/70	0/100	52/48	40/60	30/70	0/100
ZDC	10.92	8.29	6.22	0	10.92	8.29	6.22	0
ZD-1					9.8	14.5	12.43	100
ZD-2	9.8	14.5	12.43	100				
NOC (%)	83.03	83.09	83.13	83.26	83.03	83.09	83.13	83.26

Table 4. Base composition of W/O emulsions (Formulas 2a–2b) with >99% NOC.

Phase	INCI Name	Formula 2a Wt%	Formula 2b Wt%
Water	Water	29.50	
	Propanediol	3.00	
	Magnesium Sulfate	1.00	
	Biosaccharide Gum-1	0.50	
	Water (and) Ascopyllum nodosum extract	3.00	
	Preservative	0.50	
Oil	ZD-1	12.50-14.70	
	ZD-2		0.00-34.03
	ZDC	9.80-12.50	0.00-31.41
	C13-15 Alkane (and) Quaternium-90 Bentonite (and) Triethyl Citrate	4.00	
	Polyhydroxystearic Acid (and) Caprylic/Capric Triglyceride (and) Isostearic Acid (and) Lecithin (and) Polyglyceryl-3 Polyricinoleate	3.00	
	C13-C15 Alkane	Q.S.	
	Isoamyl Laurate	3.00	
Emulsifier	Polyglyceryl-6 Polyhydroxystearate, Polyglyceryl-6 Polyricinoleate	5.00	

Table 5. ZnO distribution (24.5% solid) and NOC calculation in W/O emulsions 2a and 2b.

	WO-1	WO-2	WO-3	WO-4	WO-5	WO-6	WO-7	WO-8	WO-2b	WO-3b
Ratio	100/0	50/50	40/60	30/70	20/80	10/90	5/95	0/100	50/50	40/60
ZDC	24.5	12.25	9.8	7.35	4.90	2.45	1.22		12.25	9.8
ZD-1									12.25	14.7
ZD-2		12.25	14.7	17.15	19.6	22.05	23.28	24.5		
NOC(%)	99.44	99.69	99.74	99.80	99.85	99.90	99.92	99.95	99.69	99.74

3. Results

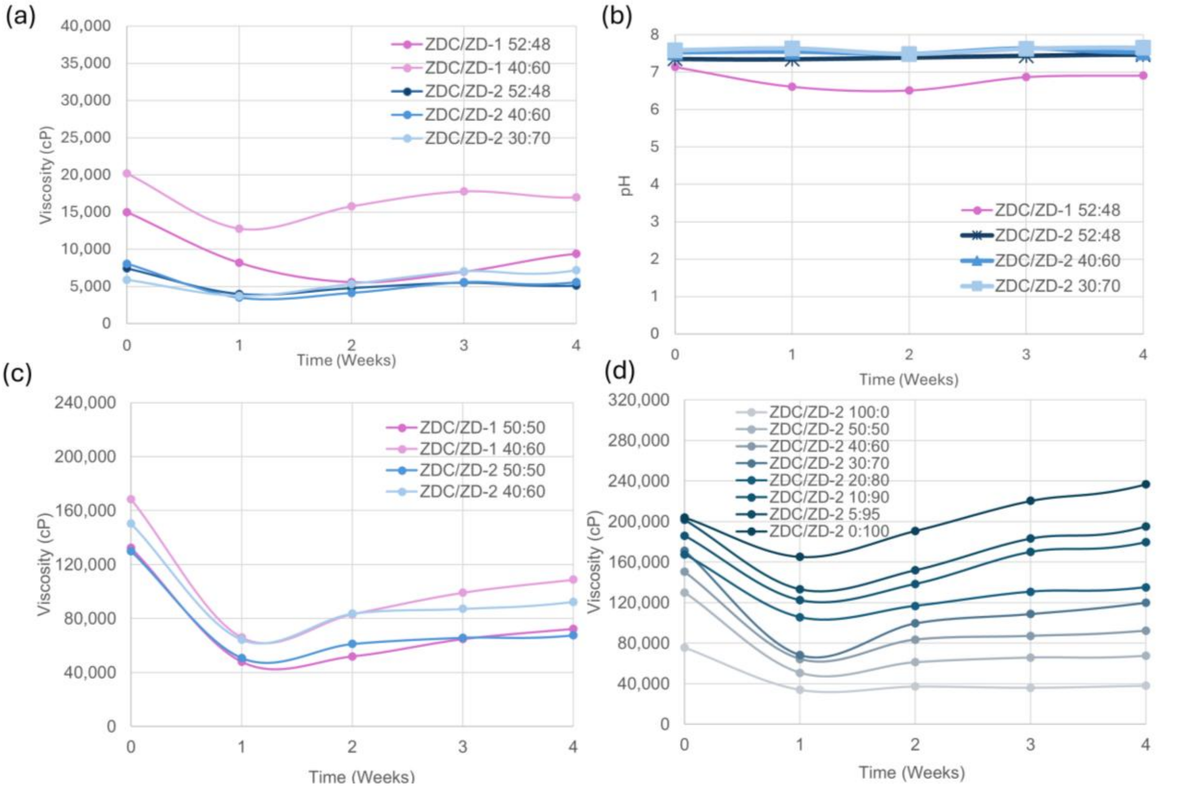

Figure 1. Four-week accelerated testing results of O/W and W/O emulsions: **(a)** Viscosity and **(b)** pH comparisons of O/W (Formula 1b, 1c) at varying ZDC:ZD-1/ZD-2 ratios (50:50 to 30:70) **(c)** Viscosity comparison of W/O (Formula 2a, 2b) at ZDC:ZD-1/ ZD-2 ratios (50:50 and 40:60); **(d)** Viscosity changes of W/O (Formula 2b) at ZDC:ZD-2 ratios (100:0 to 0:100).

3.1. Stability, viscosity and pH

In O/W emulsions, formulas containing 50–60% uZnO from ZD-1 or ZD-2 remained stable throughout the four-week accelerated study (Figure 1a). Formulas with 70% uZnO from ZD-1 exhibited phase separation by week 2, whereas blends with 50–70% uZnO from ZD-2 preserved serum-like viscosities (~5,000–9,000 cP at 1 rpm) without destabilization. At week 4, viscosities in all stable samples had decreased by 10–30 % from baseline, consistent with the ZDC-only control and indicating sustained low-viscosity behavior. This reflects the dominant influence of ZDC on viscosity. Formulas with 100 % uZnO (ZD-1 or ZD-2) separated within 24 hours, affirming that the base formula was primarily designed for ZDC. These observations help define the threshold for uZnO incorporation, with dispersion type playing a critical role.

Figure 1b shows that formulas containing ZD-2 maintained tighter pH control (6.5–6.7, ΔpH ≤ 0.2), while ZD-1-dominant systems exhibited larger shifts (ΔpH ≥ 0.6). These results indicate that TS-ZnO plays a dominant role in stabilizing pH, as formulas with ZDC alone displayed minimal fluctuations (~6.5, ΔpH 0.2–0.5), whereas 100% uncoated dispersions tended to rise above pH 7 with wider variability (ΔpH 0.4–1).

In W/O emulsions, formulas across ZDC:ZD-1 and ZDC:ZD-2 ratios demonstrated more consistent viscosity profiles (Figure 1c). ZDC:ZD-2 ratios from 100:0 to 20:80 exhibited 23–50 % viscosity reductions (Figure 1d). Conversely, the 0:100 control rose ~36 % at week 4, confirming the viscosity-stabilizing effect of TS-ZnO. Even small additions (5–10%) of TS-ZnO effectively suppress viscosity increase.

3.2 Sensory Attributes

Sensory attributes were evaluated to assess the impact of dispersion ratios on texture and user experience. In O/W emulsions, an anionic thickener (hydroxyethyl acrylate/sodium acryloyldimethyl taurate copolymer) was used to stabilize the emulsion and promote a more refreshing sensory profile. ZDC/ZD-2 formulas maintained low viscosity and delivered a fresh, fast-absorbing feel, qualities that are increasingly favored in modern skincare applications.

Compared to the smooth, lightweight feel of ZDC-only emulsions, increasing uZnO content enhanced cushion and creaminess. However, tackiness became noticeable above 70% uZnO. Overall, O/W-2 (40:60 ZDC/ZD-2) and W/O-4 (30:70 ZDC/ZD-2) were the most preferred for their optimal combination of body, spreadability, and after-feel.

3.3. In Vivo SPF

At 21% total ZnO, a 52:48 TS-ZnO:uZnO O/W blend achieved an average SPF of 44.6 without boosters, substantially higher than TS-ZnO alone (32.8). Adding a booster increased SPF to 48.4 and reduced variability (Figure 2). The synergistic effect likely results from improved ZnO particle distribution and reduced aggregation, thus enhancing UV scattering and absorption.

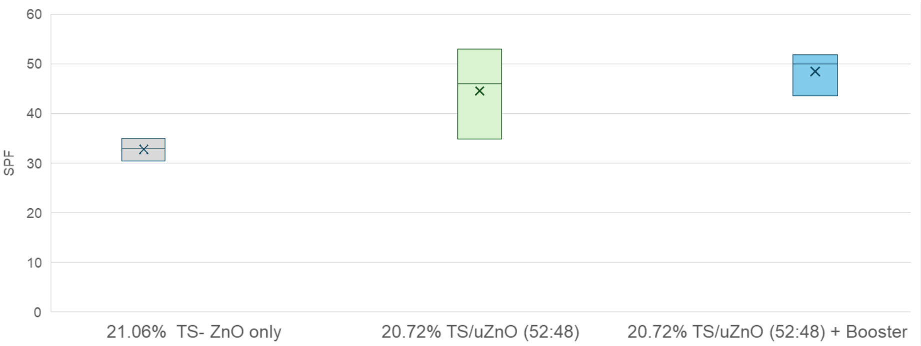

Figure 2. In vivo SPF comparison (n=3) for uZnO and TS-ZnO in O/W (Formula 1a and 1b) with and without SPF boosters.

4. Discussion

The dual dispersion strategy proved effective and versatile in both O/W and W/O emulsions, delivering superior stability, viscosity control, sensory attributes, and UV efficacy. This flexibility ensures consistent performance across a range of ZnO loadings and formulation types.

These findings suggest that surface interactions of ZnO particles play a more decisive role than Zn ion migration in governing stability, as evidenced by the consistent viscosity and pH stability patterns. The expected increases in viscosity and pH in high uZnO formulas were not observed, further supporting the greater impact of surface behavior over ionic effects on viscosity stability.

High-Natural-Content Formulation Design: Formulas were intentionally designed with high natural origin content. O/W emulsions maintained ≥83% NOC, while W/O systems exceeded 99.5%, even with up to 50% TS-ZnO, due to the minimal 1.6% triethoxycaprylylsilane content of ZDC. This meets clean-label standards without compromising performance.

Balancing the viscosity benefits of TS-ZnO (ZDC) with the transparency (minimal white cast) and texture advantages of uZnO (ZD-1, ZD-2) was central to formulation development. Based on the transparency ranking (ZD-1 > ZD-2 > ZDC), a 50:50 solid ratio served as a strong starting point for optimizing viscosity, transparency, and overall aesthetics.

Formula Performance Outcomes: Stable O/W emulsions (Formulas 1b and 1c) were developed by systematically increasing the proportion of uZnO relative to the benchmark formula (1a). The maintained stability at up to 70% uZnO from ZD-2 is particularly encouraging, as these formulas uniquely combine breakthrough serum-like consistency, minimal pH fluctuation, a desirable, fresh sensory profile, and unexpected SPF synergy. These properties are rarely achieved together in O/W ZnO-based sunscreens. Further investigation is required to optimize formulas with more than 70% uZnO.

Meanwhile, W/O emulsions demonstrated a more robust stability across a wide range of ZDC:ZD-2 ratios (100:0 to 0:100), enabling direct comparison of viscosity behavior by ZnO composition alone. As little as 5–10% TS-ZnO was sufficient to prevent viscosity increase, allowing formulators to maximize natural content without sacrificing product quality or stability.

Sensory Engineering: By varying the coated-to-uncoated ZnO ratios, formulators can fine-tune texture from fresh and light to creamy and cushioned. Formulas starting from a 50:50 solid ratio exhibited more body and cushion compared to those using ZDC-only control. Moderate uZnO levels (50–60% for O/W, 50–70% for W/O) improved transparency and texture without compromising spreadability or stability. However, higher uZnO levels introduced a heavier feel and increased tackiness as seen in O/W-3 (30:70) and W/O-5 (20:80), indicating a clear threshold beyond which sensory quality declines. Sensory differences between ZD-1 and ZD-2 were primarily attributed to their dispersion carriers: Caprylic/Capric Triglyceride in ZD-1 provides a richer, creamier feel compared to Coco-Caprylate/Caprate in ZD-2. Adjusting the coated-to-uncoated ZnO ratio empowers formulators to precisely tailor sensory profiles to meet diverse consumer preferences.

SPF Improvement: Unexpected SPF improvements in O/W emulsions likely result from broader UV coverage and more efficient ZnO distribution when combining dispersions. Historically, O/W formulas with 20–21% ZnO achieve SPF values around 30–35 (Figure 3a), with some performing as low as 15–21 due to subject variability or uneven ZnO distribution, illustrating the challenge of achieving consistent protection with mineral-only sunscreens. Remarkably, our blended O/W formula without boosters consistently achieved at least SPF 35, with two samples surpassing SPF 40 (46.00, 52.90; Figure 2), exceeding typical expectations at this ZnO level. Incorporating SPF boosters further minimized variability and delivered even more consistent results, illustrating the potential of the dual dispersion strategy to enhance SPF performance.

While the sample size was limited, the higher average SPF achieved without boosters remains noteworthy for an O/W system at this ZnO level, approaching values typically observed with 25% ZnO. This improvement is likely due to broader UV absorption enabled by the more uniform particle size distribution of the blended dispersions. Future studies should increase subject numbers, explore additional emulsion types, and further examine ZnO characteristics to optimize both SPF efficacy and formula stability.

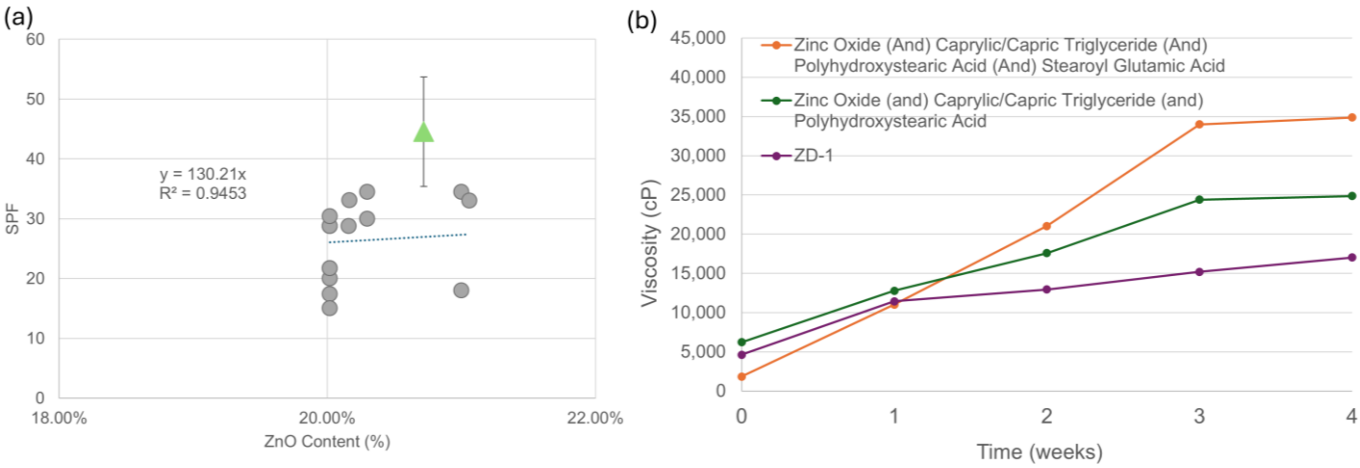

Figure 3. In vivo SPF trend analysis by ZnO usage: (a) Data from past studies for O/W emulsions formulated with either uZnO or TS-ZnO only, (grey circles: individual formulas from previous study; green triangle: TS-ZnO/uZnO formulas); (b) Viscosity comparison of ZD-1, uncoated dispersion 3, and SGA-coated ZnO dispersion in a 100% natural W/O formula.

Table 6. Comparative performance of ZD-1 and ZDC in O/W and W/O sunscreen emulsions.

Feature	100% ZD-1	Dual Dispersion (O/W)	Dual Dispersion (W/O)	100% ZDC
Viscosity Stability	Poor	Good (≥60% uZnO solid)	Good (≥60% uZnO solid, need further evaluation)	Excellent
pH Stability	Poor (ΔpH ~1)	Good (50% uZnO solid; ΔpH ~0.6)	N/A	Excellent
Sensory	Better transparency; creamiest and most rich; medium absorption	Balanced	Balanced	Good Slip, but less body/cushion and longer absorption
In Vivo SPF Range at 21% ZnO alone	17-35	35-53	-	30-35

Table 7. Comparative performance of ZD-2 and ZDC in O/W and W/O sunscreen emulsions.

Feature	100% ZD-2	Dual Dispersion (O/W)	Dual Dispersion (W/O)	100% ZDC
Viscosity Stability	Poor	Good (≥70% uZnO solid)	Good (≥95% uZnO solid)	Excellent
pH Stability	Moderate (ΔpH ~0.4)	Good (≥70% uZnO solid; ΔpH ~0.2)	N/A	Excellent
Sensory	Best transparency; creamier and more rich; quick absorption	Balanced	Balanced	Good Slip, but less body and longer absorption

Table 6 and Table 7 summarize the performance characteristics observed when combining ZDC with uncoated dispersions ZD-1 and ZD-2, respectively. These tables highlight key trends across viscosity stability, pH behavior, sensory characteristics and SPF outcomes. They also provide a direct comparison between different dispersion strategies and ZnO sources.

ZD-2 outperformed ZD-1 in stability and sensory attributes, suggesting better compatibility with ZDC. These results demonstrate that the choice of dispersing carrier and ZnO surface properties plays a critical role in formulation performance.

Formulation Implications: This study reveals that combining coated and uncoated dispersions effectively balances natural content, sensory characteristics and formulation stability. Future work should focus on expanding high-SPF mineral sunscreen options by improving the stability of high-uZnO O/W systems without compromising aesthetics.

Importantly, this work indicates that viscosity and pH stability are governed by ZnO surface properties and interfacial interactions rather than by Zn ion migration alone. As shown in Figure 3b and discussed in the Introduction, when formulating W/O emulsions with other natural ZnO dispersions, similar dispersant systems and dispersing carriers were chosen to minimize variability. Despite these controlled conditions, even naturally derived coatings such as stearoyl glutamic acid failed to prevent viscosity increases, contradicting the traditional assumption that surface coatings inherently prevent thickening. Surface chemistry thus appears to be the key in dictating emulsion viscosity and stability, more than previously recognized. Nonetheless, details such as surface treatments are often proprietary and not readily disclosed. As such, formulation development often proceeds without a complete understanding of how specific surface treatments influence long-term performance.

5. Conclusion

This study introduces a novel dual dispersion strategy combining coated and uncoated dispersions to effectively overcome major formulation obstacles in high-natural-content mineral sunscreens. The approach enables formulators to simultaneously optimize viscosity control, pH stability, UV protection, and sensory performance, even at high ZnO loadings. By pairing TS-ZnO with uZnO, the resulting emulsions remain virtually all-natural (> 99.5% naturally derived) while maintaining desirable aesthetics and application properties.

The simplicity and reproducibility of this approach, particularly its use of commercial dispersions, emphasizes its practical feasibility and high scalability for industrial implementation. In addition, recognizing the subjective nature of sensory perception, tailoring formulas to satisfy diverse consumer needs and meet market preferences is essential. This strategy offers crucial flexibility by empowering formulators to adjust dispersion ratios and achieve a variety of body, texture, and sensory profiles.

As one of the first systematic investigations of this combined approach, this research advances the understanding of how uZnO and TS-ZnO dispersion behavior impacts emulsion stability, reinforcing the critical role of surface interaction properties over traditional theories centered on the Zn ion migration.

Future work should extend this approach across other formats, such as gels, sticks, and hybrid emulsions, while embracing sustainable materials to drive the next generation of beauty and green innovation.

6. Acknowledgments

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7. Reference

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