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Unlocking the Rainbow: Advanced Technology for Diverse and Vibrant Cosmetic Colors

Claudio Pirovano[1,*], Gaetano Distefano[1], Andrea Manzo[1], Chiara Pozzi[1], Valeria Bigoni[1], Alessia Piro[1], Andrea Varè[1], Lucia Carbonara[1], Sara Bettinelli[1], Gabriele Anisia Depta, Patrizia Valsesia[1]

[1] R&I Department, Intercos S.p.A., Agrate Brianza (MB), Italy

1. Introduction

Color lies at the heart of cosmetic innovation, particularly within the ever-evolving landscape of makeup artistry. Today's discerning consumers seek a sophisticated palette of hues and finishes that go beyond mere pigmentation, reflecting the full spectrum of their diverse beauty. Pioneering brands in the beauty industry have sparked a revolution, demanding inclusive formulations that cater to a wide range of skin tones and aesthetic preferences, all while ensuring exceptional performance and a refined sensory experience.

This paper introduces a groundbreaking technological advancement [1], poised to redefine the boundaries of color in cosmetics by leveraging the surface coating process with a new class of materials specifically designed for cosmetic application.

Surface coating is a widely employed technique in cosmetics to enhance the performance of powders such as pigments and fillers. By chemically modifying the surface, the physicochemical properties of these materials can be tailored to improve characteristics like wettability, oil absorption, dispersibility, and hydrophobicity. Coating agents, typically polymers or functional molecules capable of forming covalent bonds with the pigment surface, enhance pigment compatibility, promote better dispersion, and ensure uniform blending, leading to improved wear, color payoff, and sensoriality in make-up formulations [2].

This work explores a less commonly addressed aspect of surface coating: its direct influence on the color expression of the final cosmetic product. Beyond improving performance, we investigate how surface treatments can be strategically designed to intensify, modulate, and personalize color expression, offering new opportunities for aesthetic enhancement and formulation customization.

The approach is based on the use of tailored polymeric chromophores for the surface functionalization of cosmetic powders. Polymeric chromophores [3,4] are hybrid materials that bridge the gap between conventional dyes and pigments, combining a chromophoric core with polymeric side chains (Figure 1(a)). This structure confers both intense color properties and functional versatility, improving solubility, reactivity, compatibility with diverse matrices, and overall performance. While polymeric chromophores are already established in fields such as laundry care and agrochemical formulations, their application in cosmetics remains largely unexplored.

In this study, their intrinsic versatility was leveraged to design a new generation of engineered surface coating agents for cosmetic powders. These coatings enable fine-tuning and enhancement of the substrate's intrinsic color, supporting the development of sophisticated, customized, and previously unattainable chromatic effects and finishes.

The advantages of this strategy are demonstrated through three key case studies aligned with current major trends in make-up. The first focuses on the development of new pearlescent effects, exploring novel dimensions of brilliance and pushing the boundaries of light interplay to achieve unprecedented optical results. The second case study addresses the creation of a compact matte powder palette within the red shade range, achieving deep, vibrant reds suitable for eye applications without the use of carmine. Finally, the third example showcases the development of chromatic boosters to better match and enhance all skin tones, particularly deep complexions, thereby promoting inclusive beauty formulations.

2. Materials and Methods

Chromatic powders were prepared through a coating process starting from the four chromatic oils listed in Table 1. Substrates included interference pigments with different reflection colors and particle sizes, as well as a white base for compact eyeshadows, formulated by blending synthetic mica and bismuth oxychloride in a 2:1 ratio (totaling 60 wt%), combined with silica and perlite. Additionally, a synthetic mica with an average particle size of 10 µm was employed. These substrates, which will be discussed in the case studies presented here, were coated using a high-speed mixer through sequential addition of catalyst and coating solution. After processing, the powders were dried at 80 °C for 24 hours and sieved. The prototypes of the formulations were prepared using traditional cosmetic laboratory equipment.

Table 1. INCI names of chromatic oils used for cosmetic powder surface functionalization.

	INCI
Red Chromatic Oil	Methylbenzothiazole Azotoluidine Bis-(Triethoxysilylpropylcarbamoyl Peg-5/Ppg-5 Ethanol
Violet Chromatic Oil	Bis-Hydroxyethyl/Ppg-7/Peg-4 Dicyanomethylthiophene Azotoluidine Triethoxysilylpropyl Car-Bamate
Orange Chromatic Oil	Bis-(Phenylazo Toluidine Bis-(Triethoxysilylpropylcarbamoyl Peg-5/Ppg-5 Ethanol) Sulfone
Blue Chromatic Oil	Bis-1,4(Triethoxysilylpropylcarbamoyl Poly(Diglycol Adipate) Propylamino) Anthraquinone

Color analyses of chromatic oils were carried out by preparing samples through a two-step dilution process. A determined amount of chromatic oil was weighed into a 100 mL volumetric flask using an analytical balance. The selected solvent was added to dissolve all residues, then the solution was diluted to volume and mixed thoroughly. A 10 mL aliquot was transferred into a second 100 mL volumetric flask, further diluted to volume, and mixed. UV-Vis measurements were performed on the final dilution.

Color performance of the compact powder formulation prototypes was evaluated using an X-Rite VS450 spectrophotometer, a non-contact benchtop device with a 45/0° dual-illumination geometry. Reflectance spectra were acquired and processed through dedicated software, which calculated colorimetric coordinates (L*, a*, b*, C*, h°).

3. Results

Chromatic coating oils were developed based on a previously established invention [1], through the functionalization of polymeric chromophores bearing terminal hydroxyl groups with alkoxysilane functionalities (Figure 1). The starting materials consist of commercially available polymer backbones, namely poly(ethylene glycol) (PEG) and polyesters, commonly employed in various industrial applications. These backbones were specifically tailored for cosmetic use, ensuring compliance with safety standards and optimizing functional performance.

The resulting materials comprise four primary chromatic oils, each incorporating a distinct chromophoric core, blue, red, orange, and violet. As detailed in Table 1, each chromatic oil has been assigned an INCI name and serves primarily as a wetting and dispersing agent, a function conferred by the physicochemical characteristics of the polymeric chains.

(**a**) (**b**)

Figure 1. Structural representation of (a) polymeric chromophores and (b) polymeric chromophores functionalized with alkoxysilane groups, enabling stable grafting onto cosmetic powders.

The preliminary phase of this study focused on the color characterization of the chromatic coating oils through UV-Vis spectroscopy, aimed at evaluating their optical behavior. The absorption spectra of the polymeric chromophores showed distinct maxima, directly correlating with the perceived color of each oil (Figure 2). Specifically, the red oil exhibited a maximum absorbance at 520 nm, corresponding to green light absorption; the violet oil at 572 nm, absorbing in the yellow-green region; and the orange oil at 472 nm, associated with blue light absorption. The blue oil displayed a characteristic peak at 639 nm, corresponding to red light absorption, along with a secondary peak in the UV region (256 nm), which does not influence visible coloration.

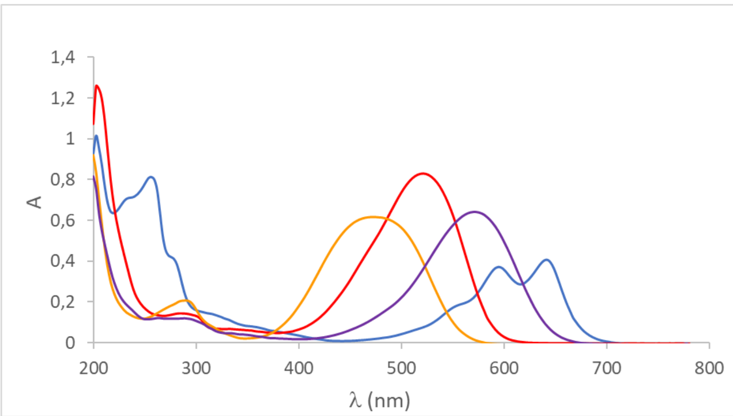


Figure 2. UV-Vis spectra of chromatic coating oils, correlating peak maxima with perceived color. The color of the profile is consistent with the color of the oil.

To quantify these observations, CIE Lab colorimetric coordinates were measured, which describe color in a three-dimensional space (Table 2): L* indicates lightness (ranging from black to white), a* describes the red-green axis (positive values toward red, negative toward green), and b* the yellow-blue axis (positive values toward yellow, negative toward blue). In addition, chroma (C*), representing color saturation, and hue angle (h°), indicating the precise hue direction, were calculated to further refine the color characterization.

All four oils showed high chroma values, particularly the orange (C* = 63.05) and violet (C* = 54.50) variants, reflecting highly saturated colors.

Table 2. Colorimetric coordinates (L, a*, b*), chroma (C*), and hue angle (h°) for the chromatic coating oils.

	L*	a*	b*	C*	h°
Red Chromatic Oil	70,0	53,8	1,7	53,8	1,8
Violet Chromatic Oil	58,9	27,7	-46,9	54,5	300,6
Orange Chromatic Oil	80,7	24,5	58,1	63,0	67,1
Blue Chromatic Oil	71,5	-19,1	-34,0	39,0	240,6

These results confirm that the polymeric chromophore-based coatings are capable of delivering transparent yet vividly colored oils, significantly expanding the chromatic range available for cosmetic powder coatings. Their high chromatic purity and visible absorption properties position them as multifunctional agents that enhance both visual appeal and formulation flexibility.

The presence of alkoxysilane functionalities on the polymeric chromophores enables their covalent grafting onto cosmetic powders bearing surface hydroxyl, through a sol-gel process. This strategy allows for the stable functionalization of a wide range of substrates, such as silicates, titania, iron oxides, glass, silica, alumina, aluminum hydroxide, and particularly pigments, including pearlescent types, through the formation of durable covalent bonds between the coating agent and the powder surface (Figure 3) [2].

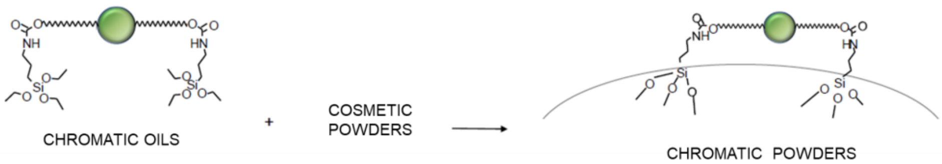


Figure 3. Surface functionalization mechanism of cosmetic powders through sol-gel reaction between chromatic oils and hydroxylated cosmetic powders.

The wide range of substrates available allows for the development of chromatic powders with diverse optical finishes, ranging from matte to satin and pearlescent, depending on the selected base material. When combined with the chromatic oils, the intrinsic optical properties of the substrates play a pivotal role in determining the final visual performance of the powders, particularly with respect to opacity, hiding power, and color saturation.

Figure 4 illustrates how the combination of appropriately selected and diverse substrates with chromatic oils enables the generation of a broad array of chromatic powders, each with distinct color characteristics. Different categories of substrates can be multiplied and enhanced in terms of chromatic expression through the interaction with chromatic oils. This approach allows for the modulation of color intensity and tone, leading to a wide spectrum of effects, from subtle light shades to deep, saturated hues.

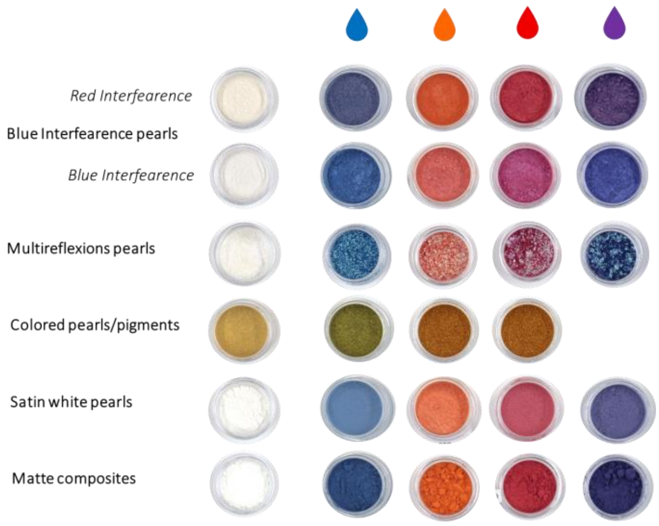


Figure 4. Chromatic powder range obtained by combining different substrates with chromatic oils.

Three case studies illustrate this strategy: innovative pearlescent effects, a matte red powder palette without carmine, and chromatic boosters to enhance all skin tones, promoting inclusivity.

Multi-dimensional perlescence

When chromatic oils are applied onto interference pearlescent pigments, a richly multi-dimensional color effect can be achieved. As illustrated in Figure 5, the combination of a transparent violet chromatic oil (used here as an example among the four chromatic oils tested) with the interference properties of the base pigment produces complex and vibrant visual outcomes. The chromatic oil selectively filters and shifts the reflected light, enhancing optical effects and often giving rise to vivid duochrome appearances.

Figure 5. Multi-dimensional perlescence: optical effects achieved by coating interference pigments with violet chromatic oil.

Notably, cooler interference tones such as blue and green are amplified, resulting in striking color transitions between purple, teal, and aqua, while warmer tones like gold are softened or altered. This simple yet powerful method allows for the design of highly versatile and customizable color palettes, opening new avenues for innovation in cosmetic formulations.

Reds for eye application

Red shades are essential in eye makeup, enhancing depth, expressiveness, and emotional impact. However, creating vibrant, stable reds presents challenges. Carmine lake, derived from cochineal insects [5], remains the only globally approved colorant for eye applications due to its vivid hue and safety profile. However, its animal origin, regulatory issues, and the growing demand for vegan and sustainable options have driven the search for alternatives. In this context, polymeric-coated powders offer a promising solution for vibrant, stable, and ethically aligned red shades, free from carmine.

In this section, we evaluate chromatic powders as promising alternatives to carmine lakes, capable of spanning a wide color gamut beyond red hues. Pressed powder eyeshadows with a matte finish were chosen as the model system for pigment testing, as they represent one of the most challenging formulations, depending solely on pigment-driven payoff, adhesion, and blendability in the absence of liquid binders, while also being among the most standardized and cost-effective cosmetic production methods.

The aim of this study was to determine, via a comprehensive color profiling exercise, the feasibility of replacing carmine by developing a prototype formulation of pressed powders that combines ease of manufacture with strong market potential.

The optimal white substrate for compact eyeshadows was formulated from a blend of synthetic mica and bismuth oxychloride (2:1 ratio, totaling 60 wt%), combined with silica and perlite to enhance coverage, tactile smoothness, and compressibility. Three monochromatic base powders were then produced via a coating process, each containing 6–10 wt% of red, violet, or orange chromatic oils on the white substrate. An additional white reference powder was prepared by incorporating 10 wt % titanium dioxide into the same substrate. These four chromatic powders served as the primary bases for developing the red-shade palette. As a benchmark, a standard formulation containing 25 wt % carmine lake, representing the maximum technically permissible loading in a compact eyeshadow, was prepared using the white substrate.

Table 3 reports the CIELAB coordinates (L*, a*, b*), the chroma (C*), and the hue angle (h°) of twelve samples based on three primary pigments (samples 1, 2, and 3) and their mixtures with white. The last row presents the color coordinates of the standard formulation containing carmine lake. The dataset spans a lightness (L*) range from 34.6 to 69.2, a chroma (C*) range from 12.1 to 54.2, and hue angles (h°) from 7.3° to 358.7°.

The chromatic distribution of these samples is illustrated in Figure 6. The a*-b* plot shows that most samples cluster within the quadrant corresponding to reddish and orange hues, with hue angles between 7° and 28°. A limited extension into the fourth quadrants (h° ≈ 294°–337°) is observed, represented by samples 3, 6, and 9, indicating reddish to purplish-bluish tones.

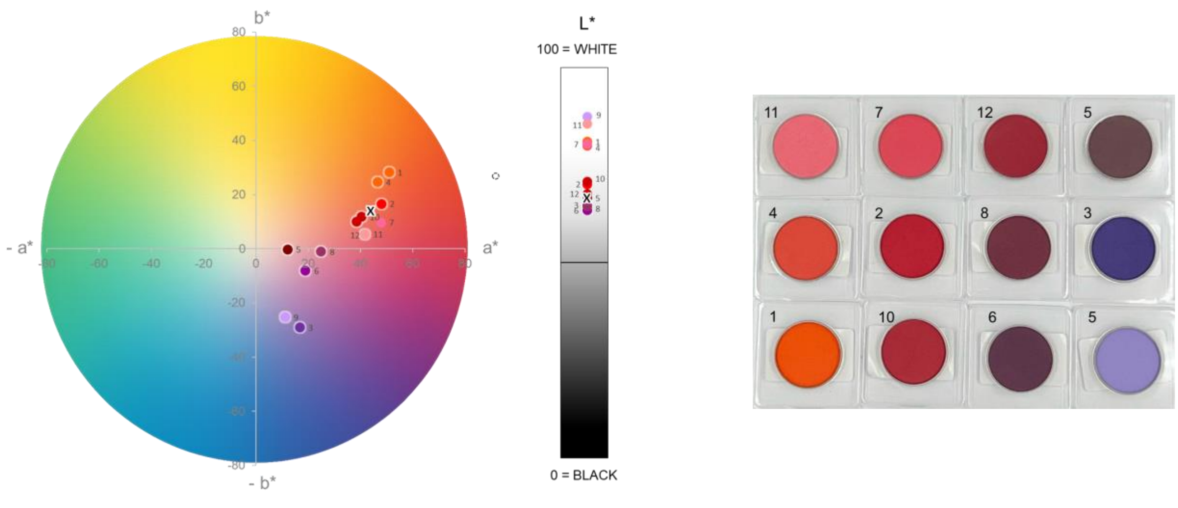
The chroma (C*) values show that the most saturated colors (C* > 50) are found among the primary samples (samples 1 and 2) and their close mixtures (sample 4). In contrast, the primary violet and mixtures with higher violet content (samples 5, 8, 9) exhibit reduced chroma.

Figure 6 also presents the lightness (L*) values across the samples. A clear positive correlation between lightness and the presence of white and orange is observed: samples with higher L* values correspond to those with greater amounts of white and orange.

The benchmark comparison with a 25% carmine lake pigment (L* = 38.9, a* = 47.1, b* = 13.1) is noteworthy. This reference point (noted in Figure 6) aligns closely with sample 2 (44.3, 47.9, 16.6) in both chroma and hue (C* = 50.7, h° = 19.1), although with slightly increased brightness. Sample 10 (45.2, 40.4, 11.8) is also near but shows a lower chroma (C* = 42.1) and slightly cooler tonality (h° = 16.3). Thus, the primary system demonstrates the ability to match carmine-like shades with minor adjustments, although achieving the exact saturation and darkness of pure carmine may require further optimization.

Table 3. Colorimetric coordinates (L, a*, b*), chroma (C*), and hue angle (h°) for the chromatic coating oils. % are weight percentages.

Sample	O	R	V	W	Color	L*	a*	b*	C*	h°
1	100%	0%	0%	0%		60,1	51,0	28,2	54,2	19,6
2	0%	100%	0%	0%		44,3	47,9	16,6	50,7	19,1
3	0%	0%	100%	0%		36,5	16,7	-29,0	33,5	300,0
4	30%	14%	0%	56%		58,4	46,4	24,6	52,7	28,1
5	50%	0%	50%	0%		39,2	12,1	-0,3	12,1	358,7
6	0%	50%	50%	0%		34,6	18,9	-8,1	20,6	336,7
7	0%	30%	0%	70%		59,1	47,8	9,7	48,7	11,5
8	0%	75%	25%	0%		36,0	24,9	-1,0	24,9	357,7
9	0%	0%	10%	90%		69,2	11,1	-25,3	27,6	293,8
10	2,25%	95,5%	2,25%	0%		45,2	40,4	11,8	42,1	16,3
11	0%	10%	0%	90%		66,6	41,6	5,4	42,2	7,3
12	0%	96%	4%	0%		40,7	38,4	10,0	39,7	14,6
Standard with 25 wt % of carmine lake (**X** in Figure 6(a))						38,9	47,1	13,1	48,9	15,5



(**a**) (**b**)

Figure 6. (a) Comparison of red shade development in pressed powder eyeshadows: chromatic powders versus standard carmine lake formulations, plotted in an a*-b* plot and L* bar chart. (b) Red shades palette.

The selected primary colors offer extensive coverage of the color spectrum, enabling the creation of pressed powder eyeshadows with a matte finish, particularly within the warm and intermediate ranges. This provides considerable flexibility for diverse color development needs. The dataset highlights strong potential for vibrant red-orange hues, with the ability to fine-tune toward pinkish and soft red tones by adding white. Additionally, it demonstrates good versatility in the purple-violet range, with the potential to achieve brownish tones as well.

Every skin tone

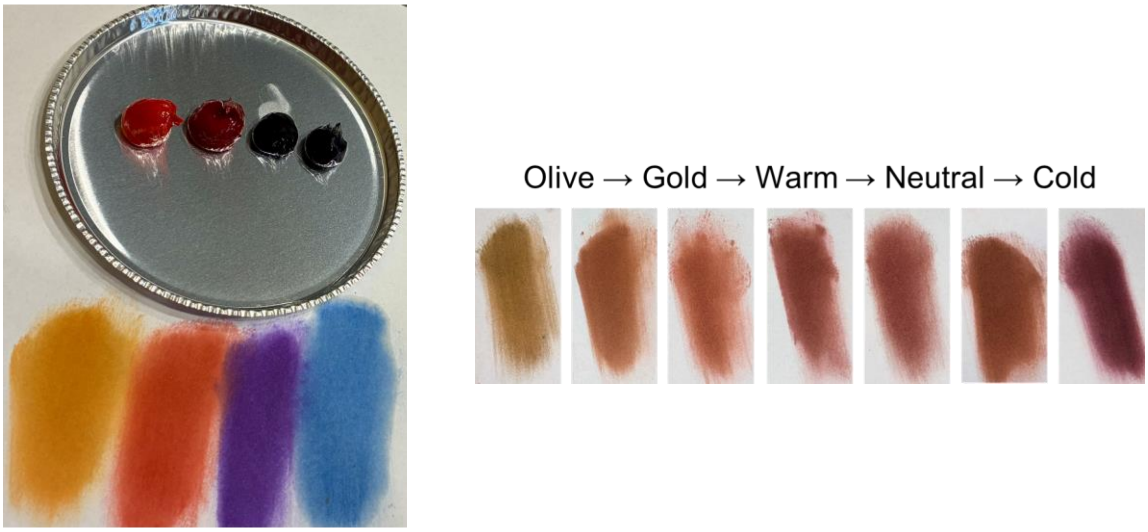
Creating inclusive foundation ranges, especially for deeper skin tones, requires ad-dressing complex color dynamics [6]. Deeper complexions are not merely darker; they encompass a wide range of undertones, including warm, cool, olive, reddish, and golden hues. Capturing these nuances is critical to avoid undesired effects such as ashy or chalky appearances, which often result from an improper pigment balance or excessive use of light fillers like. Furthermore, deeper shades require significantly higher pigment loads, up to five or six times more than lighter ones, which can affect texture, spreadability, and final aesthetic results. Traditional pigment-to-filler ratios often fail under these conditions, leading to heaviness or a mask-like effect. Tailored chromatic powders can address these challenges by providing the necessary vibrancy, coverage, and undertone modulation, supporting the development of truly inclusive formulations.

Hereafter we are showing the exercise of using synthetic mica (ca. 10 μm medium particle size, matte finish) coated with chromatic oils to assist in the obtainment of saturated and balanced undertones. Each of the four primary chromatic powders was mixed with octyldodecanol to form a uniform paste, resembling a tempera painting technique (Figure 7(a)). The exercise consisted of becoming an artist tasked with creating a personalized palette of skin undertones specifically for deep and medium-deep shades.

Figure 7(b) shows the resulting spectrum, where various undertones were deliberately constructed by mixing the primary chromatic pastes in calibrated ratios. The resulting shades reflect critical nuances found in real skin tones: olive, golden, reddish, copper, neutral, and plum-based deep hues.

This method provides a much finer control over the final chromatic quality of the foundation.Thanks to the use of chromatic oil coated synthetic mica, it becomes possible to maintain a high level of color saturation, thus preventing the common risk of the foundation appearing grayish or ashy on deeper skin tones. At the same time, the careful blending of the primary pastes allows for a precise balancing of hues, ensuring that the resulting shades remain rich and vibrant without turning muddy or overly dense. This process results in a finish that is natural, soft, and skin-like, even when dealing with highly pigmented formulas.

This artisanal approach to creating undertones shows that designing colors for deep skin shades is not a simple matter of darkening existing lighter shades. Instead, it requires a deliberate, technical craftsmanship where every nuance must be intentionally constructed to respect the complexity and beauty of real skin.This artisanal approach to undertone creation highlights the importance of treating color design in cosmetics as a highly deliberate, technical process rather than a simple darkening of lighter formulas.



(**a**) (**b**)

Figure 7. Tempera-like blending of chromatic oil-coated mica powders to create customized deep skin tone undertones: (a) primary chromatic pastes, (b) skin undertones specifically for deep and medium-deep shades.

4. Discussion

The findings of this study highlight the transformative potential of polymeric chromophore-based coatings in enhancing both the aesthetic and functional properties of cosmetic powders. Compared to conventional dye molecules, polymeric chromophores inherently offer a safer toxicological profile, as they do not penetrate the skin. This characteristic makes them an ideal choice for the development of cosmetic products, particularly for high-performance applications.

The chromatic powders derived from grafting polymeric chromophores onto selected substrates represent a significant advancement in color formulation. This capability to modulate both color intensity and finish opens new avenues for enhancing the aesthetic qualities of cosmetic formulations. The use of polymeric chromophores to achieve unique, high-impact colors offers a compelling alternative to conventional colorants, particularly lakes, which are often subject to regulatory constraints. Consequently, this approach enables the creation of vibrant, ethically sourced colors, including carmine-free reds, innovative pearlescent effects and the creation of custom colors, unlocking a rainbow of possibilities previously unexplored.

One of the highlights of this study is the application of chromatic oils onto interference pearlescent pigments, which enables the creation of multidimensional color effects. The interaction between transparent chromatic oils and interference pigments allows for the manipulation of reflected light, resulting in rich, complex, and often duochrome visual outcomes. This technique offers a powerful yet straightforward approach to developing highly customizable and visually striking cosmetic products, with considerable potential for further enhancement to achieve even more impressive multidimensional color effects.

In addition, another key aspect of the work is the development of vibrant, carmine-free red shades suitable for eye products. This research demonstrates the ability to achieve a diverse range of shades, from oranges and warm tones to deep reds and violets, within one of the most challenging formulations in terms of pigment performance: pressed powder eyeshadows with a matte finish. The outcome was not only a coloristic achievement but also the creation of a red shades palette that shows great potential in terms of cosmetic performance, combining texture, intensity, and sensory appeal in the resulting prototypes (Figure 6(b)).

When discussing the creation of inclusive cosmetic products catering to all skin tones, the ability to achieve four primary colors, bright orange, red, violet, and blue, by coating synthetic mica with chromatic oils becomes a key advantage. This approach ensures a seamless match of undertones, from warm and cool to olive and golden, particularly for deeper skin tones, which are more prone to ashy or unnatural appearances. This study highlights the potential of incorporating fillers and texturizers that not only enhance color but also provide a sophisticated, natural finish across a wide range of cosmetic products, particularly foundations. Through a highly nuanced approach, with every detail carefully engineered, this work aims to reflect and celebrate the natural diversity of complexions.

5. Conclusion

The exploration of polymeric chromophore-based coatings has unveiled a new horizon in cosmetic formulation, where color is sculpted with both scientific precision and artistic freedom. This approach enables the creation of vibrant, multidimensional hues that mirror the full spectrum of beauty, a silent tribute to the rainbow's infinite palette. By unlocking the hidden potential of cosmetic powders, we have expanded the possibilities for inclusive, expressive, and truly personalized formulations, embracing color as a dynamic and evolving expression of individuality.

6. References

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