Development of High-Performance Organic Pigment Pastes for UV-Curable Coating Systems

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This study presents the development and evaluation of optimized pigment paste formulations for UV-curable nail coatings based on seven organic pigments. The effects of the monomer-oligomer ratio, pigment loading, and dispersant concentration were investigated using planetary mixing, high-speed dispersion, and three-roll milling. Paste quality was evaluated through rheological measurements, grind gauge analysis, and opacity assessment. The results demonstrated that dispersion behavior is highly pigment-dependent and requires tailored formulation strategies. Stable, cream-like pastes suitable for automated handling processing were obtained by balancing pigment concentration, base viscosity, and dispersant performance. Three-roll milling performed at 20/10 μm roller gaps and 160 rpm resulted in only minimal changes of opacity (ΔOP = 0.27 %), indicating that organic pigments can be effectively dispersed without intensive mechanical milling. The study establishes a comparative formulation framework for organic pigments intended for the automated production of UV-curable nail coatings. The proposed approach supports the development of stable dispersions with controlled rheological and optical properties, enabling efficient and scalable industrial production of coating systems.
Keywords: UV-curable nail coatings, organic pigments, viscosity, dispersion.

1. INTRODUCTION

In recent years, UV-curable gel polishes have gained significant popularity due to their rapid curing, superior gloss, and excellent long-term wear performance [1]. Demand for durable and visually diverse UV-curable nail coatings continues to drive market growth.

UV-curable acrylate systems continue to attract significant research interest due to their widespread use in cosmetic applications and the ongoing need to improve both formulation performance and product safety [2].

UV-curable nail coatings are typically composed of acrylate-based monomers and oligomers, photoinitiators, polyurethanes, and functional additives such as wetting agents, antifoaming agents, and pigments [3]. Among these, pigments are critical for achieving the desired color and visual appearance of the final product [4, 5].

Since pigments cannot be directly incorporated in their dry powder form, efficient dispersion is a key step in coating formulation [5]. Many pigments require wetting and dispersing agents to achieve compatibility with UV-curable systems [5, 6]. Therefore, manufacturers commonly use pre-dispersed pigment pastes in an acrylate medium, which promote pigment stabilization and uniform distribution within the polymer matrix [4, 5].

A major challenge in paste formulation is balancing high pigment loading with suitable viscosity. Highly viscous systems hinder application and process automation [7, 8], while low pigment content reduces opacity and color intensity [5, 6]. Therefore, pigment pastes must provide both suitable rheological properties and consistent optical performance [9].

Pigment paste performance is commonly evaluated through coating properties such as color uniformity, graininess, opacity, and pigment dispersion quality. This enables quality verification prior to the paste's incorporation into the final formulation [10].

Pigments used in UV-curable systems are commonly classified as organic pigments, inorganic pigments, and lacquers based on their chemical composition [11]. The present study concentrates on organic pigments.

Organic pigments are characterized by bright colors and high color strength [12]. They typically have a smaller primary particle size and a larger specific surface area than inorganic pigments. As a result, organic pigments exhibit a lower refractive index and higher transparency [13]. Their high surface energy promotes interparticle attraction and agglomeration, which complicates uniform dispersion in UV-curable systems [14]. Therefore, efficient wetting and dispersant stabilization are essential.

Commercial pigment pastes typically exhibit high viscosity, which restricts their usability to manual operations and complicates scale-up. Automation is important for improving process precision, efficiency, and reproducibility, but conventional equipment is often unsuitable for handling highly viscous systems [15]. In-house production can improve process control and formulation flexibility. However, there is limited published information describing optimized formulation and processing strategies for organic pigment dispersions in UV-curable systems. In particular, systematic comparisons

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of the effects of pigment type, dispersant selection, and formulation parameters on dispersion behavior remain scarce.

Accordingly, this research aims to develop and optimize pigment paste formulations suitable for UV-curable gel coatings, focusing on seven organic pigments. The selected organic pigments are commercially relevant cosmetic-grade materials that comply with applicable EU cosmetic regulations. All pigments were sourced from Sensient, a major European manufacturer of cosmetic-grade pigments, ensuring consistent quality and industrial relevance.

The study aims to establish an optimal formulation and processing strategy for organic pigment pastes intended for UV-curable nail coatings. It investigates the relationship between paste composition and physico-chemical properties, and evaluates the effects of dispersion techniques on pigment dispersion quality.

2. MATERIALS AND METHODS

2.1. Materials

All coating ingredients were selected to comply with the requirements of the EU Cosmetics Regulation. The pigment paste base was formulated using aromatic monofunctional methacrylate (monomer, purity > 98 %, *Sartomer*) [16] and bifunctional aliphatic urethane acrylate (oligomer, *Sartomer*).

A Type I phosphine oxide photoinitiator (*IGM Resins*) and silicon dioxide (> 99.8 %, *Sensient*) [17] were used as functional components. Three dispersants supplied by *BYK Additives* were included: Dispersant 1 – fatty acid-modified polyester; Dispersant 2 – high-molecular-weight polymer; Dispersant 3 – acrylic block copolymer.

Seven organic pigments were used, all supplied by *Sensient* and identified by their Color Index (CI) numbers: Unipure Blue LC520 (CI 75470), Unipure Orange LC226 (CI 15985), Unipure Red LC320 (CI 75470), Unipure Yellow (Yellow 5 Lake) LC125 (CI 19140), Unipure Red LC303 (CI 15850), Unipure Red LC322 (CI 45380), and Unipure Red LC3079 (CI 15850).

2.2. Equipment

A precision laboratory balance (PR 1000.R, Radwag, Poland) was used for weighing raw materials. Pigment pastes were mixed using a planetary mixer (Hauschild SpeedMixer®DAC 250.3 FVZ, Hauschild GmbH & Co KG, Germany) and a high-speed disperser (Palpostrast 56 KK-300, Dispermill, Netherlands). Milling was performed using three-roll mills (S65, Shandong Sayhi Machinery Co., China; ZYTR-BOE, ZYE, China).

Rheological measurements were obtained using a Kinexus KNX5112 rheometer (NETZSCH-Gerätebau GmbH, Germany). Films with controlled thicknesses were prepared using an automatic film applicator (Byko-drive, BYK-Gardner, Germany). UV curing was performed under a UV/LED lamp (KP800LED, YI Liang Electron Technology Co., China). The light stability of the pigmented coatings was evaluated using a Xenon test chamber. Coating quality was evaluated using a digital microscope (ANESOK®321, Inskam, USA), a Hegman grind gauge (BYK, Germany), and a Datacolor 200 spectrophotometer (Datacolor, Switzerland). Unless otherwise stated, all measurements were performed in triplicate, and the reported values represent mean values.

2.3. Wetting test

The wetting behavior of dry pigment powders was evaluated using a semi-quantitative visual method. A drop of coating liquid was placed next to the pigment powder on a glass plate and gently drawn toward the powder using a wooden spatula. The interaction between the liquid and pigment surface was visually observed. To reduce subjectivity, a five-level rating scale was applied, where score 1 indicated no wetting and score 5 represented rapid spreading and complete penetration into agglomerates.

2.4. Preparation of pigment pastes

Based on the wetting test results, four different paste bases were prepared (Table 1).

Table 1. Proportions of paste base components

Base	A	B	C	D	E
Monomer, %	40.0	50.0	75.0	81.0	80.9
Oligomer, %	55.7	45.0	20.0	15.0	14.1
Photoinitiator and silicon dioxide, %	4.3	5.0	5.0	4.0	5.0

Pigment powders were added to the paste base and premixed using a planetary mixer for 4 min at 1800 rpm. The dispersant was then added, and the mixture was processed again under the same mixing conditions. When required, additional dispersion was carried out using a high-speed disperser.

The premixed dispersions were further processed with a three-roll mill. The paste was manually applied between the first and second rolls. Temperature was monitored throughout milling to avoid excessive heating.

Milling was performed in four sequential stages with progressively reduced roll gaps: 150/75 μm, 80/40 μm, 20/10 μm, and 10/5 μm. The rotation speeds were 200, 200, 160, and 120 rpm, respectively. At each stage, the dispersion passed through the rolls twice.

2.5. Rheology and grind gauge measurement

The milled paste was incorporated into the coating base to obtain a formulation containing 10 wt.% pigment paste. Dispersion fineness was evaluated using a Hegman grind gauge according to ASTM D1210 standard method [18]. A small amount of the pigmented formulation was placed at the deepest end of the gauge and drawn across the scale with a steel scraper. The position where streaks or particle agglomerates first appeared was recorded as the grind value. Rheological analysis was performed at 25 °C using a parallel-plate geometry with a measurement gap of 0.2 mm. Viscosity was recorded at shear rates of 0.1, 1, 10, and 100 s^{-1}.

2.6. Optical and visual evaluation

Coating films were prepared to evaluate dispersion before and after three-roll milling. Test formulations were prepared by adding 0.5 wt.% pigment paste and 2 wt.% TiO_2 white pigment to the coating base.

The mixture was homogenized for 4 min using a planetary mixer. Films were then applied onto a substrate with an automatic film applicator (Byko-drive) to obtain a wet film thickness of 200 µm. The coatings were cured for 60 s under a UV/LED lamp (λ = 400 – 410 nm).

The cured films were visually inspected, both with and without magnification, to detect pigment agglomerates. Samples exhibiting noticeable graininess were further examined using a digital microscope. This enabled differentiation between flocculated and agglomerated structures and estimation of particle size.

Opacity (OP) was determined using a spectrophotometer by measuring CIE Y reflectance values on black (Y_b) and white (Y_w) backgrounds. The contrast ratio was calculated according to Eq. 1 based on ASTM D2805 method [19].

$$OP\ (\%) = (Y_b/Y_w) \times 100\%. \quad (1)$$

2.7. Accelerated stability testing

Stability was assessed through three approaches: thermal stability, color stability after aging, and light stability. For thermal stability, pigment pastes and pigmented formulations were stored at 50 °C in a laboratory oven. Pigment pastes were evaluated after 2 weeks, while pigmented systems were monitored for up to 3 months. At defined intervals, viscosity was measured and samples were visually examined for sedimentation and phase separation.

Color stability after thermal aging was evaluated by comparing coatings prepared from stored samples (50 °C, 3 months) with freshly prepared references. Color differences were determined using spectrophotometric measurements. Light stability was tested by exposing cured films to Xenon irradiation for 2 h. After exposure, color changes were measured spectrophotometrically.

For comparative evaluation, corresponding formulations prepared using commercially available pigment pastes were also produced and subjected to the same thermal aging and Xenon light stability tests as the formulations containing the developed pigment pastes.

3. RESULTS AND DISCUSSION

3.1. Wetting test

The wetting behavior of the pigments was evaluated using a semi-quantitative five-level rating scale. The monomer without dispersing additives demonstrated the highest wetting efficiency (score 5), characterized by rapid spreading and fast penetration into pigment agglomerates. In contrast, formulations containing dispersants showed lower wetting scores (3), accompanied by slower spreading and delayed penetration behavior.

Efficient wetting depends on interfacial compatibility and surface energy balance between the liquid phase and pigment surface [20, 21]. The observed wetting efficiency of the monomer reflected strong interfacial compatibility with the investigated pigments, which contributed to improved dispersion during mechanical processing.

Although the applied wetting assessment provided practical comparative information for formulation screening, the method remains semi-quantitative. Additional techniques, such as contact angle or surface energy measurements, could provide a more detailed characterization of wetting mechanisms and should be considered in future studies.

3.2. Paste composition formulation

The optimal paste composition for each pigment was determined through a systematic series of formulation experiments. The base type, pigment loading, dispersant type, and dispersant concentration were varied to evaluate their influence on paste consistency and processability. The resulting systems were visually classified as liquid, cream-like, semi-solid or solid.

The results demonstrated that each organic pigment required an individual formulation strategy. Differences in pigment surface properties, particle size, and pigment-medium interactions influenced wetting behavior, dispersion efficiency, and rheological properties. Similar pigment-dependent behavior has been reported previously [22].

Initial screening experiments identified bases B and D as the most suitable systems for organic pigments. This can be explained by the influence of base composition on pigment wetting and particle stabilization. The polarity and viscosity of UV-curable systems are known to strongly affect particle distribution, agglomeration behaviour and dispersion stability [22], which is consistent with the present findings.

Further optimization was performed using base B or D in combination with dispersant 1 or 2. Pigment and dispersant concentrations were adjusted to maximize pigment loading while maintaining a workable consistency, preferably cream-like (Table 2). Vv – v v

Table 2. Formulation adjustment of pigment pastes for individual pigments

Base	Pigment	Pigment, wt.%	Dispersant type	Dispersant, wt. %	Consistency
B	LC226	49	1	2.4	cream-like
	LC320	50	–	–	
	LC520				
D	LC125		2	2.5	liquid
	LC303				cream-like
	LC322	45	1	1.4	semi-solid
	LC3079	44	2	2.8	cream-like

For most pigments examined (4 of 7), dispersion was carried out using the less viscous base D. Although liquid systems were not considered ideal, they remained processable and were therefore not further modified. In contrast, semi-solid and solid systems required optimization because of their limited handling and incorporation properties.

The type of dispersant played a critical role in pigment stabilization and overall dispersion quality [22]. Both dispersants enabled the formation of cream-like pastes under suitable formulation conditions. However, further optimization focused on formulations containing dispersant 1 because of its practical suitability for large-scale manufacturing and automated processing. These formulations were subsequently processed using a three-roll mill, and their consistency after milling was evaluated (Table 3).

Table 3. Optimized formulations of milled organic pigment pastes prepared using Dispersant 1

Base	Pigment	Pigment, wt.%	Dispersant, wt.%	Consistency
B	LC226	43	4.0	cream-like
	LC520	49	2.4	
	LC320			
D	LC125		2.5	liquid/cream-like
	LC303			cream-like
	LC3079	44	4.1	
	LC322			liquid/cream like

Formulations prepared without dispersant generally resulted in semi-solid or solid systems, whereas the addition of dispersant significantly improved paste consistency. This effect can be explained by the adsorption of the dispersant molecules onto the pigment surface, which reduces particle-particle interactions and promotes deagglomeration [20]. Improved particle distribution resulted in more homogeneous and workable systems suitable for further processing.

Dispersant 1 enabled the formation of cream-like pastes; however, in some cases this required either a lower pigment loading, the use of a less viscous base, or higher dispersant concentrations (up to 4.1% relative to total paste mass for the red pigment LC3079). Comparable consistency could also be achieved under adjusted conditions using alternative dispersant systems. The effectiveness of a dispersant is closely related to its molecular structure, which determines its ability to adsorb onto the pigment surface and provide steric stabilization in the polymer medium [14]. This stabilizing effect prevents particle re-agglomeration while maintaining acceptable rheological properties.

At higher dispersant concentrations, an increase in viscosity was observed, indicating a non-linear relationship between dispersant content and rheological behavior. Similar behavior has also been reported in the literature [20] and is commonly associated with excess non-adsorbed dispersant remaining in the continuous phase, which increases intermolecular interactions [14]. At low concentrations, dispersant molecules adsorb onto the pigment surface, reducing particle-particle interactions and facilitating deagglomeration. However, once the available pigment surface becomes saturated, additional dispersant remains in the liquid phase and may contribute to increased viscosity. This suggests that dispersant concentration must be carefully balanced to achieve sufficient stabilization without negatively affecting flow behavior [23].

Repeated laboratory-scale preparations performed under identical processing conditions showed similar dispersion behavior and no significant differences in the evaluated properties, indicating good reproducibility of the developed systems.

3.3. Effect of three-roll milling on pigment dispersion

After optimizing pigment wetting, the influence of three-roll milling on dispersion quality was investigated. The optimal milling regime was achieved with a 20 µm gap between the first and second rolls and a 10 µm gap between the second and third rolls. The process was carried out at a rotation speed of 160 rpm and repeated twice.

During three-roll milling, the pigment paste is exposed to high shear stress within the narrow gaps between rotating rolls. These forces progressively break down pigment agglomerates and improve particle distribution. The stepwise reduction in roll gap increases shear intensity, allowing more efficient disruption of remaining agglomerates and resulting in a more homogeneous dispersion [14].

To evaluate the effect of milling on optical properties, pigmented base formulations were prepared using the organic pigment Unipure Red LC320. Two systems were investigated: one containing either 5 wt.% LC320 pigment and another containing 0.5 wt.% LC320 pigment combined with 2 wt.% TiO_2 pigment. The opacity values before and after milling are presented in Table 4.

Table 4. Opacity (OP) measurements of LC320 pigment pastes before and after three-roll milling

Pigmentation in the color base	OP of pigmented color base applications, %				
	Mean value before milling OPb	SD, %	Mean value after milling OPa	SD, %	ΔOP (OPa-OPb)
5 wt.%	49.97	0.55	50.25	0.32	0.27
0.5 wt.%+2 wt.% (white pigment)	80.37	0.71	80.44	0.18	0.07

In contrast to typical observations reported in the literature, where milling leads to a significant increase in opacity due to improved dispersion [24], no notable change in opacity was observed for the LC320 containing system after milling. This suggests that the pigment was already well dispersed before milling and that large agglomerates were largely absent.

The addition of TiO_2, however, resulted in a pronounced increase in opacity. The increase in opacity is attributed to the high refractive index of TiO_2, which enhances light scattering and improves visual coverage [24].

These findings indicate that the efficiency of three-roll milling depends strongly on the initial dispersion state and pigment characteristics. While milling is a critical step for systems containing poorly dispersed pigments, its impact may be limited when the pigment is already finely distributed. Therefore, optimal dispersion requires careful control of both formulation parameters and processing conditions.

3.4. Stability of pigment dispersions

After formulation optimization, the stability of pigment pastes and pigmented systems was evaluated under accelerated conditions. Thermal, color, and light stability were assessed to estimate the long-term performance of the developed formulations.

Storage at elevated temperature (50 °C) showed that both pigment pastes and pigmented formulations remained physically stable over the test period. No visible sedimentation or phase separation was observed. Viscosity changes were minimal and remained within the acceptable range, indicating that the internal structure of the dispersions was preserved.

Thermal aging of pigmented systems for up to 3 months resulted in only minor color changes. The measured color differences were within acceptable limits and comparable to

those typically observed in commercial systems. This indicates that pigment particles remained well distributed in the matrix, with no significant aggregation or degradation during storage.

To further evaluate practical performance, corresponding formulations prepared using commercially available pigment pastes were tested under the same thermal aging and light stability conditions. The developed pigment pastes exhibited comparable color stability and overall performance, with no substantial differences observed during the evaluation period. These results indicate that the developed dispersions provide a level of stability suitable for practical application in UV-curable nail coating systems.

Exposure to Xenon light did not cause noticeable color changes, confirming good photostability. This is particularly important for UV-curable coatings, where prolonged light exposure can affect visual performance.

Accelerated testing at elevated temperature is commonly used to predict long-term behavior of coating systems, as higher temperatures promote diffusion, aggregation, and degradation processes [25]. The stability observed under these conditions indicates that the developed dispersions are resistant to such changes.

The observed results are likely the consequence of an optimized combination of formulation composition and processing conditions. Effective wetting ensures uniform distribution of pigment particles in the base [20]. Dispersant adsorption stabilizes the particles by reducing attractive interactions and preventing re-agglomeration. High-shear milling further contributes by breaking down remaining agglomerates, resulting in a fine and stable dispersion. Overall, the developed systems exhibit good thermal, rheological, and photostability. These properties are essential for maintaining consistent processing behavior and visual performance during storage and application.

4. CONCLUSIONS

This study demonstrated that the successful development of organic pigment pastes for UV-curable systems requires a careful balance between pigment loading, base composition, dispersant concentration, and processing conditions. The results showed that formulation parameters cannot be universally applied across different pigments, as pigment-specific interactions strongly influence rheological behavior, dispersion quality, and optical performance.

The findings further indicate that dispersant selection and concentration are critical not only for achieving stable dispersions but also for controlling viscosity. The results indicate that overly high dispersant levels can adversely affect rheological behavior, highlighting the necessity of formulation optimization for each specific pigment system.

Although three-roll milling improved dispersion quality, its effectiveness depended on the initial state of pigment wetting and stabilization. This emphasizes that mechanical processing alone cannot compensate for insufficient formulation design.

Optical performance was strongly affected by pigment composition. The incorporation of TiO_2 significantly increased opacity due to enhanced light scattering, confirming its role as an effective opacity modifier in pigment systems.

The developed formulation strategy provides a practical framework for designing organic pigment dispersions under industrially relevant conditions. Although the study focused on UV-curable nail coatings, the identified relationships between pigment properties, dispersant performance, rheological behavior, and processing conditions are also relevant to other UV-curable coating systems and pigment-containing formulations. The work demonstrates that successful dispersion development requires an integrated approach combining formulation design and processing optimization rather than the adjustment of individual parameters alone. By systematically comparing seven organic pigments, this study contributes to a broader understanding of pigment-specific formulation behavior and guides the development of stable, reproducible, and scalable dispersion systems.

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