Spectroscopic Characterization of Commercial UV-Curable Gel Polish, Identifying Acrylate Monomers and Additives Using NMR Technique

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http://doi.org/10.5755/j02.ms.42439

Received 11 August 2025; accepted 18 November 2025

This study investigates the composition and structure of commercial UV-curable gel polish formulations using advanced spectroscopic techniques. Five commercially available gel polish products and eight raw materials were analyzed using nuclear magnetic resonance (^{1}H, ^{13}C, ^{31}P NMR). Spectral comparisons revealed characteristic signatures of acrylates, urethane acrylates and functional additives, including 2-hydroxyethyl methacrylate (HEMA) and diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO). Component identification was achieved by matching unique chemical shifts and signal multiplicity with reference raw materials. The results demonstrate that all commercial formulations contained HEMA, a known skin sensitizer, and several incorporated phosphorus-based photoinitiators such as TPO, associated with potential toxicological and environmental concerns. By providing a detailed structural fingerprint of key monomers and additives in UV-curable systems, this study contributes to improving formulation transparency, enabling better risk assessment, and supporting the development of safer alternatives in nail coating technologies.
Keywords: UV-curable nail coatings, sensitizers, cosmetic toxicology, acrylate monomers.

1. INTRODUCTION

UV-curable gel polishes represent a rapidly expanding segment within the cosmetic industry, valued for their rapid polymerization kinetics, extended wear resistance, and broad aesthetic versatility [1 – 4]. Originally developed for industrial applications, such as coatings, paints, inks and dental restorative materials. UV-curable acrylate systems have been utilized in dentistry for over 80 years [5, 6]. In the past two decades, these materials have been adopted in cosmetic formulations, particularly in nail care, where their performance characteristics have proven highly desirable [7, 8].

Although some studies have explored the potential of UV-curable coatings as drug delivery systems for topical treatment of nail disorders [1, 9], their predominant use remains aesthetic. However, the transition of these materials from industrial to cosmetic applications raises significant safety considerations. Many of the raw materials used-particularly monomers and photo initiators – were not initially intended for direct contact with human tissues. Over the past five years, a notable increase in reports of adverse reactions, including allergic and irritant responses, has been documented, prompting a surge in toxicological investigations into these coatings and their components [10 – 19].

The global market for UV-curable nail gel coatings reflects this surge in popularity. Estimated at approximately USD 55.6 million in 2023, the market is projected to grow to USD 88 million by 2030 [7, 20], underscoring strong consumer demand for organic polymer coatings with enhanced performance features [21 – 24]. This growth trajectory, however, is paralleled by mounting concerns regarding the biological safety of these products. Adverse health effects-such as allergic contact dermatitis, onycholysis, and cutaneous sensitization-have been increasingly reported in both consumers and professional users [12, 13, 16, 17].

In response to these developments, comprehensive characterization of gel polish formulations is essential. A detailed understanding of the chemical composition of commercial products is critical to identifying which ingredients are most frequently used and which may be associated with undesirable biological effects. Such knowledge is pivotal for guiding the substitution of high-risk substances and fostering the development of biocompatible alternatives that do not compromise on performance.

Commercial gel polish formulations are complex mixtures of oligomers, monomers, photoinitiators, and additives, designed to ensure rapid curing, strong adhesion to the nail plate, and long-term durability. Among these, urethane acrylate-based oligomers and monomers are commonly employed due to their favorable mechanical and adhesion properties, particularly on keratinous substrates [21 – 23]. However, detailed formulation data are often withheld for proprietary reasons, complicating independent safety assessments.

From a toxicological perspective, particular attention has been paid to acrylate monomers such as 2-hydroxyethyl methacrylate (HEMA) and isobornyl methacrylate (IBOMA), both of which are established skin sensitizers [13-18]. Similarly, photo initiators such as diphenyl(2,4,6-trimethylbenzoyl) phosphine oxide (TPO) are known to exhibit cytotoxic and photo allergenic properties [10 – 13]. These risks are exacerbated in occupational settings, such as nail salons, where repeated exposure via skin contact or inhalation may result in cumulative health effects for both

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professionals and clients [10, 11, 13]. In recognition of these toxicological concerns, the use of TPO in cosmetic products is prohibited in the European Union as of 1 September 2025, pursuant to Commission Regulation (EU) 2025/877, which amends Annex II of Regulation (EC) No 1223/2009. This ban further underscores the critical importance of accurate product composition analysis and ingredient identification in UV-curable gel polishes to ensure regulatory compliance and consumer safety.

Given these concerns, it is essential to deploy robust analytical techniques capable of resolving complex formulation matrices. Nuclear Magnetic Resonance (NMR) is well-established, non-destructive tool that enables qualitative and quantitative analysis of organic compounds in complex mixtures [25, 26].

This study aims to characterize five commercial UV-curable gel polish formulations using 1D NMR techniques-including ^{1}H, ^{13}C, and ^{31}P nuclei spectra-and to compare the spectral data against a panel of eight known raw materials. The objectives were to identify key formulation components, assess the use of acrylate monomers and phosphine oxide-based photo initiators, and evaluate the formulation similarities and potential toxicological implications of these widely used coatings.

2. MATERIALS AND METHODS

2.1. Materials

Five gel polish products and twelve commercially available raw materials (Table 1) were selected for the study.

Table 1. Raw materials analyzed in UV curing nail coatings

No.	Product INCI name
1	Urethane acrylate 1
2	Urethane acrylate 2
3	Hydroxyethyl methacrylate (HEMA)
4	Phosphate Acrylate Monomer
5	Isobornyl methacrylate (IBOMA)
6	Diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide
7	Acrylate copolymer 1
8	Acrylate copolymer 2

2.2. Nuclear magnetic resonance spectroscopy

Nuclear magnetic resonance spectra (^{1}H NMR and ^{13}C NMR) were recorded using a Bruker Avance NEO 500 spectrometer. The ^{1}H NMR spectra were acquired at 500 MHz, calibrated against the residual solvent signal ($CDCl_3$:δ = 7.26 ppm). The ^{13}C NMR spectra were recorded at 126 MHz and calibrated using the solvent's ^{13}C signal ($CDCl_3$:δ(C) = 77.16 ppm). Chemical shifts (δ) are reported in parts per million (ppm) and coupling constants (J) are given in Hz.

2.3. Component identification

Product spectra were compared against raw material references. Unique signals and characteristic multiplicity patterns (e.g., doublets, triplets) were used to identify matches. Component confirmation was strengthened by observing correlations in both ^{1}H and ^{13}C spectra.

3. RESULTS AND DISCUSSION

3.1. Results

Comparative NMR analysis was conducted for all five gel polish products using ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy. The respective spectra are shown in Fig. 1, Fig. 3, and Fig. 3. Distinct similarities and differences were observed among the product formulations. Initial analysis of the ^{1}H NMR spectra (Fig. 1) revealed that Gel Polish 2 exhibited the simplest composition, as indicated by the lowest number of signals and overall spectral complexity. The spectral region between 5.5 – 6.5 ppm confirmed differences in acrylate compositions across products, with Gel Polish 2 primarily containing a single acrylate, alongside minor additions of others. In contrast, Gel Polish 1 featured the most complex composition with multiple acrylate signals, suggesting the presence of at least 2 – 3 different monomers.

The aromatic region (7.5 – 9.0 ppm) also revealed variability between products. Gel Polish 1 and Gel Polish 5 shared a characteristic additive identified as TPO, while Gel Polish 2 contained a structurally similar aromatic compound. Gel Polish 4 and Gel Polish 3 presented lower intensities in the aromatic region; the signals in Gel Polish 4 differed in chemical shift, suggesting structural variation, while those in Gel Polish 3 were too weak for definitive assignment.

Additional differences were observed in the region 3.3 – 3.7 ppm, where Gel Polish 2 and Gel Polish 3 displayed similar signals, likely arising from related structural components. Conversely, Gel Polish 1, 4, and 5 exhibited overlapping signals in the aliphatic region (0.7 – 1.7 ppm), suggesting the presence of different oligomers in their formulations.

The ^{13}C NMR spectra (Fig. 2) provided further compositional insights. The 120 – 140 ppm region, representative of acrylate double bonds, showed fewer signals in Gel Polish 2 and Gel Polish 3, corroborating the simplified monomer composition inferred from ^{1}H NMR. Additional similarities between these two products were evident near 75 ppm and 15 – 20 ppm. Products Gel Polish 1, 4, and 5 exhibited characteristic signal clusters around 20 ppm, indicating the presence of additional oligomeric structures.

^{31}P NMR analysis (Fig. 3) revealed the presence of phosphorus-containing additives in three products: Gel Polish 2, 4, and 5, each containing a single organophosphorus compound detectable by NMR. These were most likely phosphorus-based components, while Gel Polish 1 and 3 showed additional signals corresponding to phosphate-based additives, suggesting dual phosphorus functionalities.

After defining key similarities and differences between products, the next step was to identify specific components by comparing product spectra with raw material references. Using unique signals (non-overlapping chemical shifts or distinctive multiplicities), it was possible to assign identities with high confidence. In Gel Polish 5, eight raw materials were identified based on comparative analysis of ^{1}H and ^{13}C NMR spectra (Fig. 4 and Fig. 5).

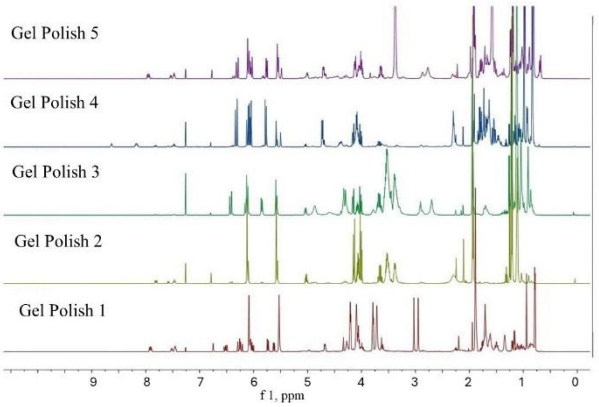

Fig. 1. Comparison of ^{1}H NMR spectra of various products ($CDCl_3$)

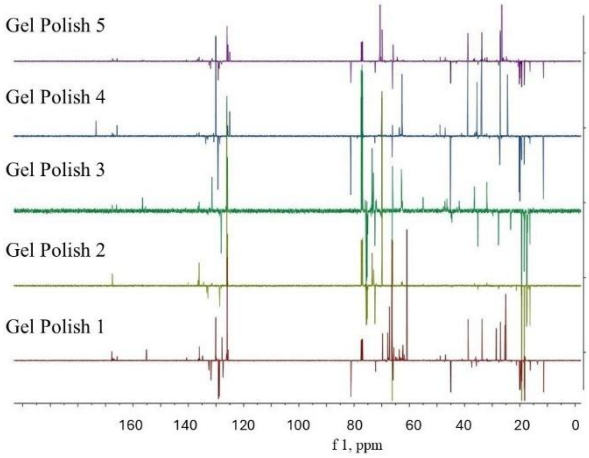

Fig. 2. Comparison of ^{13}C NMR spectra of various products ($CDCl_3$)

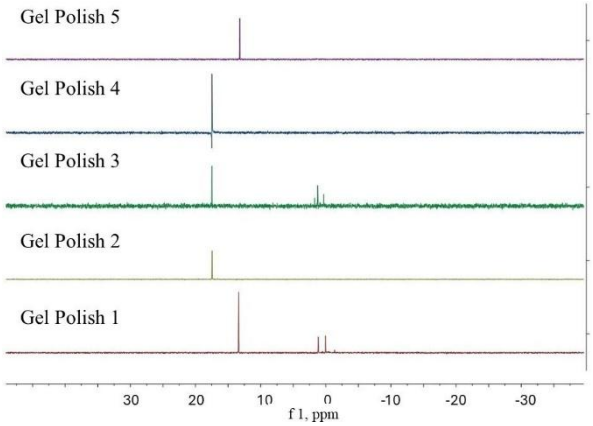

Fig. 3. Comparison of ^{31}P NMR spectra of various products ($CDCl_3$)

The intensity of observed signals depended on the concentration of each component, with signals from substances present at concentrations below 5 % often falling below NMR detection thresholds.

Similar comparative analyses were performed for the remaining four commercial products. In some cases, more components were detected via ^{13}C NMR than ^{1}H NMR due to reduced overlap and a broader chemical shift range in the carbon spectra. All five commercial products were confirmed to contain HEMA. IBOMA was unambiguously identified in two of the samples.

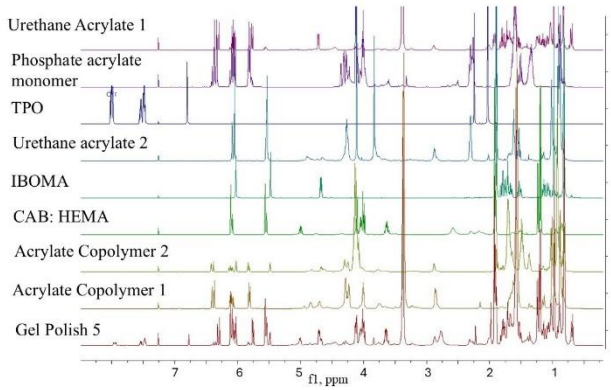

Fig. 4. Comparison of the ^{1}H NMR spectra of Gel Polish 5 and various raw materials ($CDCl_3$; the first spectrum from the bottom is that of the product, the others are raw material spectra)

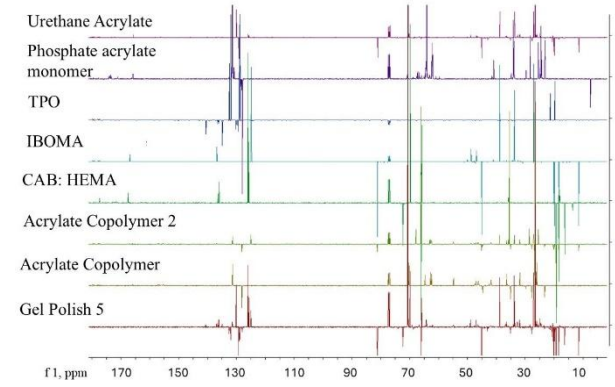

Fig. 5. Comparison of the ^{13}C NMR spectra of Gel Polish 5 and various raw materials ($CDCl_3$; the first spectrum from the bottom is that of the product, the others are raw material spectra)

3.2. Product-specific results

Gel Polish 1: HEMA was confirmed by characteristic vinyl proton signals at 5.5 and 6.1 ppm and two doublets at 1.2 ppm. IBOMA was identified via double bond signals overlapping with HEMA, a distinctive doublet of doublets at 4.1 ppm, a broad signal at 1.0 ppm, and a doublet at 0.8 ppm. TPO was confirmed by aromatic peaks (7.4 – 8.0 ppm) and singlets at 2.2 and 2.0 ppm. Urethane acrylates showed multiplet structures at 6.3, 6.1, 5.8 ppm, and in the region 1.0 – 1.8 ppm. These were further supported by ^{13}C signals at 130, 80, 39, 34, and 27 ppm (urethane acrylates), 45 and 11 ppm (IBOMA), and 72 – 66 ppm (HEMA).

Gel Polish 2: HEMA was confirmed through vinyl signals at 5.5 and 6.0 ppm, multiplets between 4.2 – 4.0 ppm, and a broad aliphatic signal at 1.0 ppm. Aromatic proton signals attributable to diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO) were primarily detected in the ^{1}H NMR spectrum within the aromatic region, while corresponding aromatic carbon resonances appeared in the ^{13}C NMR spectrum between 125 and 140 ppm, confirming the presence of TPO in the formulation.

Gel Polish 3: Besides HEMA, acrylate copolymers were identified by their vinyl signals at 5.7, 6.2, and 6.5 ppm and additional characteristic signals at 4.3 and

0.9 – 1.1 ppm. ^{13}C NMR confirmed the presence of acrylate copolymer 2 through signal clusters at 67, 35, 26, and 19 ppm.

Gel Polish 4: Contained acrylate copolymer 2 (multiplets at 5.5 – 6.5 ppm and 0.9 – 2.0 ppm), HEMA, and IBOMA. Additionally, ^{13}C spectra indicated the presence of urethane acrylates, consistent with other high-performance formulations.

Gel Polish 5: contained the highest number of identifiable components, with at least eight raw materials confirmed through spectral overlap. HEMA was identified by vinyl proton signals at 5.5 and 6.1 ppm and doublets at 1.2 ppm. IBOMA showed overlapping double-bond resonances with HEMA, a doublet of doublets at 4.1 ppm, and aliphatic signals at 1.0 and 0.8 ppm. Urethane acrylates exhibited multiplets at 6.3 – 5.8 ppm and 1.0 – 1.8 ppm, supported by ^{13}C signals at 130 – 27 ppm (urethane acrylates), 45 and 11 ppm (IBOMA), and 72 – 66 ppm (HEMA).

Table 2 summarizes the identified raw materials per product. HEMA was found in all five products, and IBOMA was confirmed in at least two. TPO was detected in the aromatic region of ^{1}H spectra and further confirmed by carbonyl and aromatic signals in ^{13}C NMR.

3.3. Discussion

The identification and comparative analysis of commercially available UV-curable gel polish products revealed significant differences in formulation complexity and component diversity. These findings align with prior research demonstrating the wide variability of acrylate monomer and oligomer compositions used in light-curable systems [2, 4, 5]. Spectral comparison with reference materials allowed for the identification of key ingredients, such as HEMA, IBOMA, urethane acrylates, and TPO, which are frequently reported in cosmetic and dental UV systems [5, 6, 8].

The presence of HEMA and other methacrylates is consistent with known commercial formulations, which often use these compounds for their reactivity and mechanical performance, but also raise concerns about sensitization and allergenicity [6, 8]. The identification of urethane acrylates, characterized by multiplet structures in the ^{1}H and ^{13}C spectra, is supported by earlier studies that demonstrate their flexibility and strong adhesion properties [3, 4].

The identified phosphorus-containing compounds included diphenyl(2,4,6-trimethylbenzoyl)phosphine oxide (TPO) and a phosphate acrylate monomer.

Their identification through ^{31}P NMR highlights their significance as adhesion promoters in complex systems. Similar analytical strategies have been employed in studies analyzing commercial dental adhesives and nail gels, confirming the presence of these additives despite formulation secrecy [8, 11].

Spectroscopic technique such as ^{1}H, ^{13}C, and ^{31}P NMR has proven indispensable in the deconvolution of complex cosmetic formulations. This aligns with recent literature, where the combination of FTIR, GC-MS, and NMR was successfully used to characterize commercial UV-curable nail coatings [26, 27]. However, it is important to note the limitations in signal detection for components present at concentrations below 5 %, as their signals may not be observed due to method sensitivity [26].

Overall, the current findings not only support previous observations but also provide a practical framework for qualitative compositional analysis of gel polish systems. Such analytical insight is crucial for product development, quality control, and ensuring user safety in the rapidly growing market of UV-curable cosmetics.

4. CONCLUSIONS

This study characterized five commercial UV-curable gel polish formulations using ^{1}H, ^{13}C, and ^{31}P NMR enabling the identification of key monomers, photo initiators, and additives. HEMA was present in all products, while IBOMA, urethane acrylates, and phosphorus-based Photo-initiators were detected in selected formulations. The results highlight substantial variability in formulation complexity and confirm the presence of sensitizing compounds such as HEMA and TPO, emphasizing the importance of ongoing toxicological evaluation. The presented analytical approach offers a reliable framework for quality control, formulation transparency, and the development of safer alternatives in UV-curable cosmetic coatings.

Table 2. Raw materials analyzed in UV curing nail coatings

Gel polish	^{1}H, ppm		^{13}C, ppm		^{31}P, ppm	
1	7.4 – 8.0	TPO			2.2, 2.0	TPO
	6.3, 6.1, 5.8, 1.0 – 1.8.	Urethane acrylates	130, 80, 39, 34, 27	Urethane acrylates		
	5.5, 6.1, two doublets at 1.2	HEMA	72 – 66	HEMA		
	Doublets at 4.1, 1.0, 0.8	IBOMA	45, 11	IBOMA		
2	7.4 – 8.0	TPO	125, 140	TPO	2.2, 2.0	TPO
	5.5, 6.1, 1.2	HEMA				
3	5.7, 6.2, 6.5	Acrylate compolymer 1	67, 35, 26, 19	Acrylate compolymer 2		
	5.5, 6.1, two doublets at 1.2	HEMA	72–66	HEMA		
4	Multiplets at 5.5 – 6.5 ppm and 0.9 – 2.0 ppm	Acrylate copolymer 2	130, 80, 39, 34, 27	Urethane acrylates		
	5.5, 6.1, two doublets at 1.2	HEMA				
	Doublets at 4.1, 1.0, 0.8	IBOMA				
5	5.5, 6.1, two doublets at 1.2	HEMA	72 – 66	HEMA		
	Doublets at 4.1, 1.0, 0.8	IBOMA	45, 11	IBOMA		
	6.3 – 5.8, 1.0 – 1.8	Urethane acrylates	130 – 27	Urethane acrylates		

Acknowledgments

The research was supported by CFLA project No 5.1.1.2.i.0/2/24/A/CFLA/004 “Development of safe and effective UV-curable coatings free from TMPTA, MEHQ, TPO, and HEMA”.

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